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AN EXPERIMENTAL STUDY OF THE SHOCK WAVE IN FREE AIR FROM SPHERI--ETC(U)
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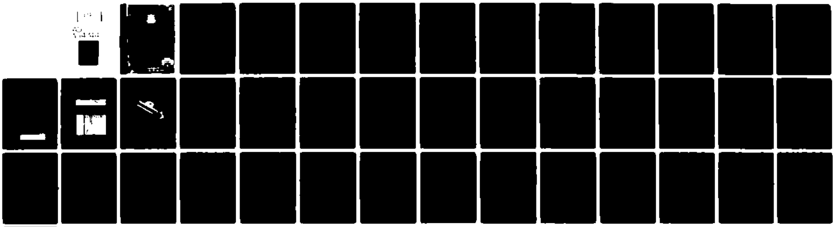

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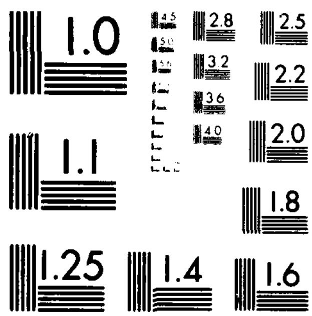

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United Kingdom Atomic Energy Authority

AWRE, Aldermaston

AWRE REPORT NO. 01/73

An Experimental Study of the Shock Wave in Free Air from Spherical Charges of TNT and 60/40 RDX/TNT

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Approved for issue by

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CONTENTS

SUMMARY

Results are presented which give information on those aspects of the shock wave which are of the most common interest, namely: peak pressure, positive impulse, positive duration, maximum negative pressure, shape of the pressure-time curve and information on the secondary shock.

An equation for the peak pressure-distance curve is given and a comparison of results is made.

The values of constants which define the shapes of pressure-time curves are given.

All measured values are displayed graphically and photographs of actual records are reproduced.

1. INTRODUCTION

This report presents the results of experimental work carried out by R Potter and C V Jarvis in 1953 and 1954.

It contains basic information on the two commonly-used explosives RDX/TNT 60/40 and TNT; the latter is used as a standard.

At the time these experiments were carried out investigations had been made on the behaviour of shock waves from charges placed on or near the ground and little information was available on the effects from charges fired sufficiently high above the ground to eliminate its effect and to be virtually in free air.

The pressure gauges and recording equipment used were of the latest improved pattern and formed the basis for those used today.

2. OBJECTS OF THE INVESTIGATION

The series of experiments was intended to supply basic data, on all aspects of the blast wave from charges exploded in free air, which might be of practical and theoretical importance.

The quantities investigated were:-

(a) Peak overpressure.

(b) Radius-time curve of the primary shock.

(c) The impulse of the positive phase.

(d) The duration of the positive phase.

(e) The secondary shock.

(f) The maximum negative phase pressure.

(g) The shapes of the pressure-time curves of the primary shock.

3. METHODS AND APPARATUS

Major difficulties were caused by the height at which it was required to mount the charge and gauges, and the relative flimsiness of the structure necessary to avoid spurious reflections.

In the first experiment using charges of RDX/TNT 60/40 the height was just under 40 ft. Although all the gauges and charges were in the same horizontal plane they were not located in a straight line. Distances were therefore determined photographically from ground level using a suitable scaling rod. The arrangement is shown in figure 1.

In the second experiment using charges of TNT it was found convenient to reduce the height to about 32 ft and locate the gauges and charge in the same horizontal and vertical planes. This height was still sufficient to avoid interference from ground reflections. The modification enabled distances to be determined more accurately and wind corrections to be made more easily (figure 2).

The wind correction to distance measurements were made by the appropriate subtraction or addition of the product of wind speed and time of arrival of the shock wave at the gauge for each distance. Firings were preferably carried out when the wind speed was low.

The pressure transducers used were type B2 piezo-electric gauges (figure 3) and recording was by means of multi-channel oscillograph records. The pressure gauges have been fully described in reference [1] (in which it is referred to as the H3 gauge).

Improvements incorporated in the second experiment were a photo-cell zero time marker and millisecond time markers on the recording traces.

The charges were nominal 8½ lb spheres of RDX/TNT 60/40 and 8 lb spheres of TNT respectively made from accurately machined hemispheres. Initially they were cemented with CE/TNT eutectic but, after satisfactory compatibility tests were carried out, distrene cement was used.

At the beginning of the second experiment on TNT, a number of coarse grained charges were fired in addition to a number of fine grained charges to see whether there was a significant difference. These rounds indicated that there was no significant difference, but nevertheless the results were obtained mainly from fine grained charges, apart from those few coarse grained charges mentioned. It was necessary to use a 5 oz RDX/TNT booster and a No. 3 electric detonator with the TNT.

According to a generalised law of similitude, distance and time may be scaled as the cube root of the weight of the charge or its energy equivalent and therefore directly proportional to its linear dimensions.

This has been verified experimentally by R G Sacks for explosive weights of 1 - 20000 lb.

4. RESULTS AND DERIVED DATA

The measurements quoted were obtained by reduction to the 1 lb scale by dividing time and distance scales by the appropriate values of $W^{1/3}$, where W is the weight of the charge.

Variations in atmospheric pressure have been allowed for on the pressure-distance graph by dividing all pressures by the appropriate atmospheric pressure, but the slight modifications in time and distance scales have been ignored.

In the case of TNT, variations of atmospheric temperature (and hence sound speed) have been allowed for on the radius-time graph by multiplying all times by the appropriate sound speed for that round. For the TNT experiment the average atmospheric pressure during the firings was 14.78 psi and the average sound speed 1119.6 ft/s.

4.1 Peak pressure-radius

This was regarded as the most important information to be obtained and the results were fitted by least squares to a curve of the form

$$\frac{p_s}{p_o} = \frac{a}{R} + \frac{b}{R^2} + \frac{c}{R^3} \text{ [2]},$$

where p_o is the atmospheric pressure and p_s the peak overpressure at the shock front.

It was assumed that the standard deviation of a pressure value was proportional to the pressure. A study of figures 1(a) and (b) will show this assumption to be quite reasonable, as the points are scattered fairly evenly about the curves which are plotted on a logarithmic scale, where equal intervals represent equal percentages, and scatter must be approximately a constant percentage of the pressure. The standard error of the curve [3] is given in figures 4(a) and (b) and is less than 1% over the whole range. Figure 5 gives the result for TNT with pressure expressed in psi.

In figure 6 the ordinates give the ratios of the distances at which the same peak overpressures are obtained for pentolite [4] and RDX/TNT, using TNT as the standard.

To make a comparison between two explosives a ratio curve may be integrated between the appropriate pressure limits and the result divided by the pressure range; this leads to a factor of equivalence, ie, two explosions can be called equivalent when the mean scaling factor between defined pressure limits is unity.

Explosion 1 ≡ explosion 2 if

$$\frac{1}{p_2 - p_1} \int_{p_1}^{p_2} \frac{R_1}{R_2}\, dp = 1,$$

where the pressure p is obtained at a distance R_1 from explosion 1 and R_2 from explosion 2 and p_1 and p_2 define the range of pressure.

Peak pressure for the two explosives reduced to the scale for 1 lb give:

Experiment 1 RDX/TNT

$$\frac{P_s}{P_o} = \frac{2.071}{\left(\frac{R}{W^{1/3}}\right)} + \frac{18.871}{\left(\frac{R}{W^{1/3}}\right)^2} + \frac{115.17}{\left(\frac{R}{W^{1/3}}\right)^3} \text{ (150 recordings).}$$

Experiment 2 TNT

$$\frac{P_s}{P_o} = \frac{2.208}{\left(\frac{R}{W^{1/3}}\right)} + \frac{13.627}{\left(\frac{R}{W^{1/3}}\right)^2} + \frac{111.01}{\left(\frac{R}{W^{1/3}}\right)^3} \text{ (200 recordings).}$$

Equivalence factor for the pressure range $\frac{P_s}{P_o} = 0.05 - 3.9$,

1 lb of RDX/TNT 60/40 ≡ 1.5 lb TNT,

also 1 lb of pentolite [4] ≡ 1.22 lb TNT.

The pressure-distance relations for the two experiments are shown in figures 4(a) and (b). The standard error [3] was of the order of 2% for RDX/TNT and less than 1% for TNT. This reflects the increased accuracy obtained with the improved layout arrangement.

4.2 Radius-time

Curves for primary and secondary shock for RDX/TNT are shown in figure 7(a). The broken line represents the point at which the pressure in the wave first returns to atmospheric. For distances greater than 15 ft on the 1 lb scale this point is obtained by extrapolation as explained in section 4.3.

For TNT the results are shown in figure 7(b). The recorded arrival times T are multiplied by the appropriate sound speed.

4.3 Positive duration-distance

The results and approximate mean curve (fitted freehand) are shown in figures 8(a) and (b). For distances greater than 15 ft on the 1 lb scale, the secondary shock has entered the positive phase and hence the duration of the positive phase is suddenly increased. Instead of quoting this increased value a small extrapolation of the p-t record

was made and the results quoted are estimates of what the duration would have been in the absence of the second shock. This is obviously somewhat artificial but bearing in mind that the duration is used principally for specifying wave shapes it is probably more useful than the actual positive duration.

4.4 Decay constant-distance

The decay constant θ has been taken as the time for the overpressure to decay to 1/e th of its peak value. This is discussed further in section 4.8.

The recorded values and mean curves are shown in figures 9(a) and (b).

4.5 Positive impulse-distance

The measured values and curves are shown in figures 10(a) and (b). Only the primary wave impulse has been considered.

4.6 Time separation and ratio of overpressure of primary and secondary shocks

The results for RDX/TNT 60/40 are shown in figures 11(a) and (b), and those for TNT in figures 12(a) and (b). It will be seen that over most of the range the secondary shock strength is about 20% of the primary shock.

The apparent scatter in results of the time separation is an indication of variation between rounds, as the results for any one round lie on a smooth curve. This inter-round variation is thought to be due to imperfect detonation.

4.7 Maximum negative pressure

The results are shown in figures 13(a) and (b).

4.8 Pressure-time curve shape factor

In 1946 Friedlander [5] used a formula for the pressure-time curve of a blast wave in air which was a fairly simple and qualitatively correct representation.

(i) $y = (1 - x)e^{-x}$.

More recently, modified forms of his equation have been suggested. For example,

(ii) $y = (1 - x)e^{-cx}$

and (iii) $y = (1 - x)^k e^{-kx}$,

where $y = \frac{p}{p_s}$,

$x = \frac{t}{\tau}$,

p = overpressure,

p_s = peak overpressure,

t = time, measured from instant of arrival of primary shock,

τ = duration of the positive phase,

c and k are constants for any one wave shape but may vary with distance from the charge.

Considering the difficulties experienced in measuring positive durations, namely, the necessity of extrapolation and the small slope of the pressure-time record in the region where the excess pressure has fallen to zero which makes accurate measurement very difficult, it was decided to measure the time at which the pressure had fallen to e^{-1} of its peak value although the wave shape is not purely exponential. This time is defined as the decay constant. At high pressure, however, where the negative phase pressure is only a small percentage of the peak pressure, the exponential form may be quite an adequate approximation. At lower pressures the Friedlander equation $y = (1 - x)e^{-x}$ is an adequate representation of the important portion of the wave if it is fitted to have the correct decay constant rather than the correct duration. This gives the relationship $y = (1 - [t/\tau'])e^{-(t/\tau')}$, where $\tau' = 2.31\theta$, and θ is the decay constant as defined above. This formula is easier to deal with than are the modified forms, which are discussed below; since these expressions take no account of the second shock their use in considering damage etc is usually unwarranted.

By plotting $\log (y/(1 - x))$ against x for a given wave-shape it is apparent from the resulting curve, which is approximately a straight line, that form (ii) will give a fairly adequate representation. In a similar manner plots of $\log y$ against $\log [(1 - x)e^{-x}]$ show that the form (iii) could also represent the data fairly well. The results from the first experiment have been used for the analysis. The resulting graphs for records 1, 5, 12 and 16 of figures 14(a) and (b) are given in figures 15(a) and (b), and the derived values of c agreed with the curve of figure 16(a). The values of k for the records 1, 5, 12 and 16 of figures 14(a) and (b) are shown in figure 15(c).

From the peak pressure, positive duration and impulse data, or from the plots just suggested, values of c and k as functions of distance from the charge can be obtained. Only the value of c has been fully investigated and it was found that c was obtained with slightly less scatter when deduced from the peak pressure p_s, decay constant θ, and positive duration τ; the values so derived are given in figure 16(a). An attempt to use the peak pressure, positive impulse and decay constant, and hence avoid using the positive duration which is the most difficult of the measurements, was unsuccessful because impulse/$p_s\theta$ is insensitive to changes in c, ie, small errors in the ratio give large errors in c. A number of other methods of determining c, or k, are possible, eg,

measurements of two ordinates in addition to the peak, measurements of the peak slope etc, but none of these alternatives has been investigated.

It was considered that expressing c as an algebraic function of peak pressure would not be useful if the expression were at all complex, but, from a plot of c as a function of peak pressure, c was found to be proportional to the square root of p_s and the simple relation $c = 1.4(p_s)^{\frac{1}{2}}$ (p_s in atmospheres) is a very good representation of the data.

It is a point in favour of using the form containing c, that k cannot be represented by such a simple formula.

For TNT the value of c as a function of distance is given in figure 16(b) and a function of peak pressure in figure 16(c). From figure 16(c) it can be seen that $c = 1.32p_s^{0.563}$ approximately but since this formula is not simple it is of limited value.

4.9 Reproduction of actual records

4.9.1 RDX/TNT

In figures 14(a) and (b) sixteen records obtained at different distances are reproduced to give an indication of the quality of the records and to show actual wave shapes. These records have been selected and are somewhat better than average, but records which are appreciably inferior to these have been rejected and the quoted data are all from records of good quality.

4.9.2 TNT

Photographs of typical pressure-time records are shown in figure 17 where the millisecond markers can be seen on each trace together with the time zero marker.

5. COMMENTS AND CONCLUSIONS

No full comparison with other data has been attempted and discussions and deductions have in general been avoided in order that the experimental evidence could be presented in a compact manner.

The choice of TNT as a standard of reference seems somewhat unfortunate because of the difficulty of proper initiation. Attempts to initiate it without a booster were unsuccessful. The method of boosting appears to have a marked effect on the performance and may partially explain the differences between different sets of observations. The information from different observers does nevertheless agree fairly well.

6. LIST OF SYMBOLS USED

R = radius of primary shock

W = weight of spherical charge of RDX/TNT 60/40

p_s = peak overpressure of primary shock

p_o = atmospheric pressure

$t(R)$ = time taken to travel to radius R

τ = duration of positive phase

θ = decay constant (defined in section 4.4)

I = positive impulse of primary shock

t = time measured from instant of arrival of primary shock

p = overpressure at time t

$y = \frac{p}{p_s}$

$x = \frac{t}{\tau}$

For c and k, see section 4.8.

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1. R C Jefferys, K J Jarvis and P J Deas: "The Measurement of Air Blast: The H3 Blast Gauge". ARDE Memo MX 54/60

2. R G Stoner and W Bleakney: J Appl Phys, 19 (July 1948)

3. Whittaker and Robinson: "Calculus of Observations". Blackie, Chap IX

4. Kirkwood and Brinkley: "Theoretical Blast Wave Curves for Cast TNT". OSRD Report No. 5481 (August 1945)

5. Proc Roy Soc A, 186 (1946)

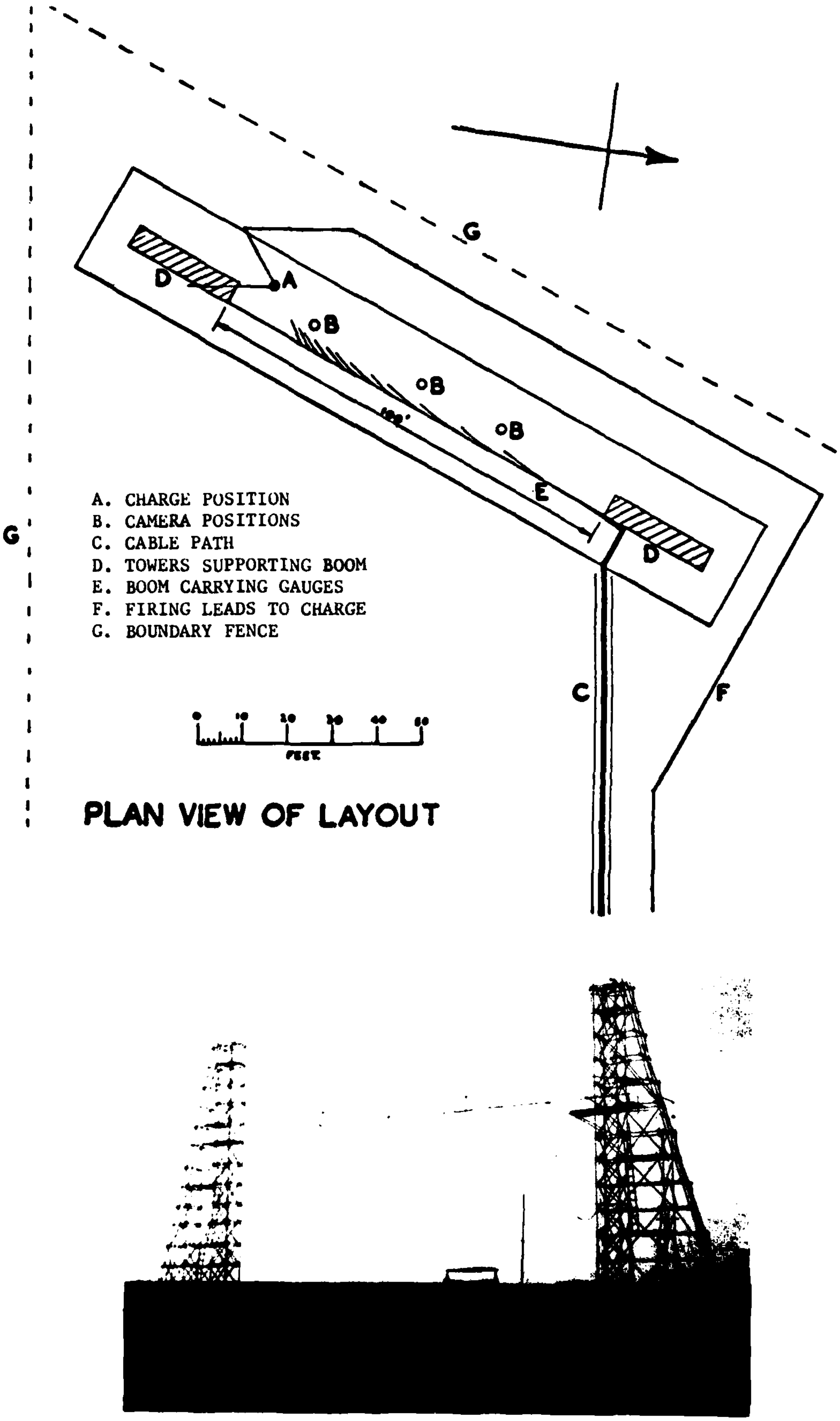
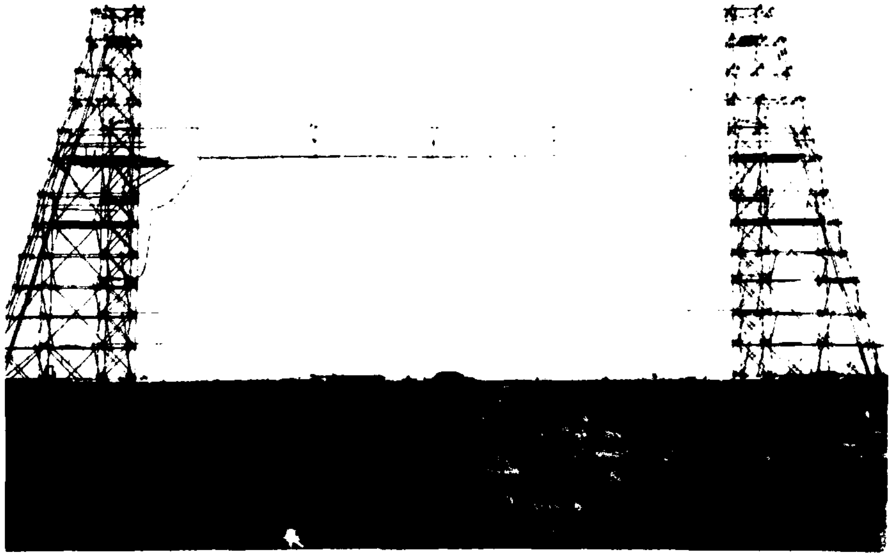
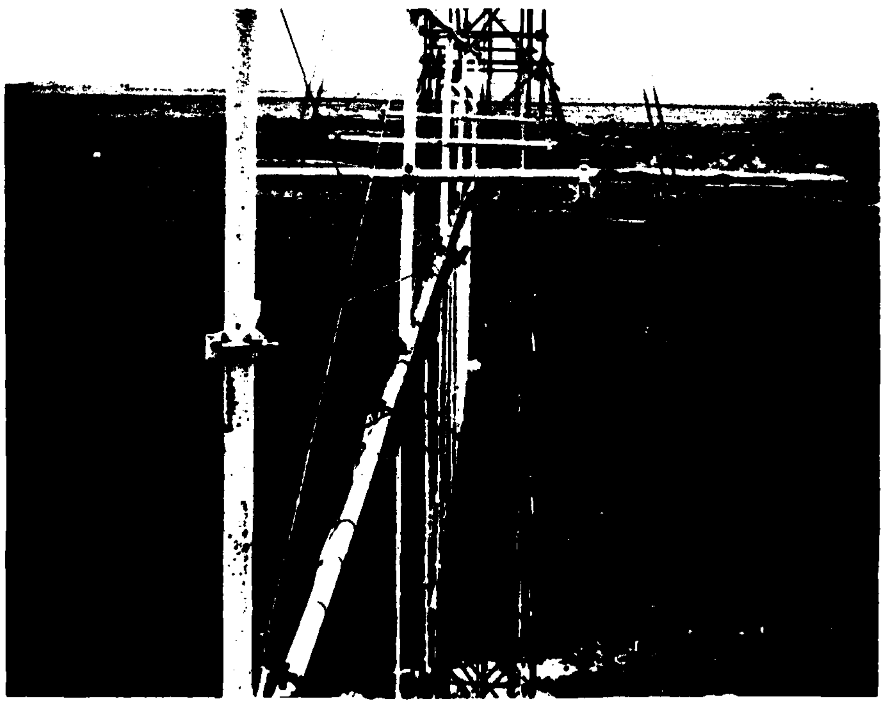


FIGURE 1. ARRANGEMENT OF CHARGE AND GAUGES FOR RDX/TNT 60/40



GENERAL VIEW OF TOWERS LAYOUT FOR TNT



VIEW ALONG BOOM SHOWING GAUGES AND CHARGE IN POSITION

FIGURE 2

FIGURE 3. B2 GAUGE

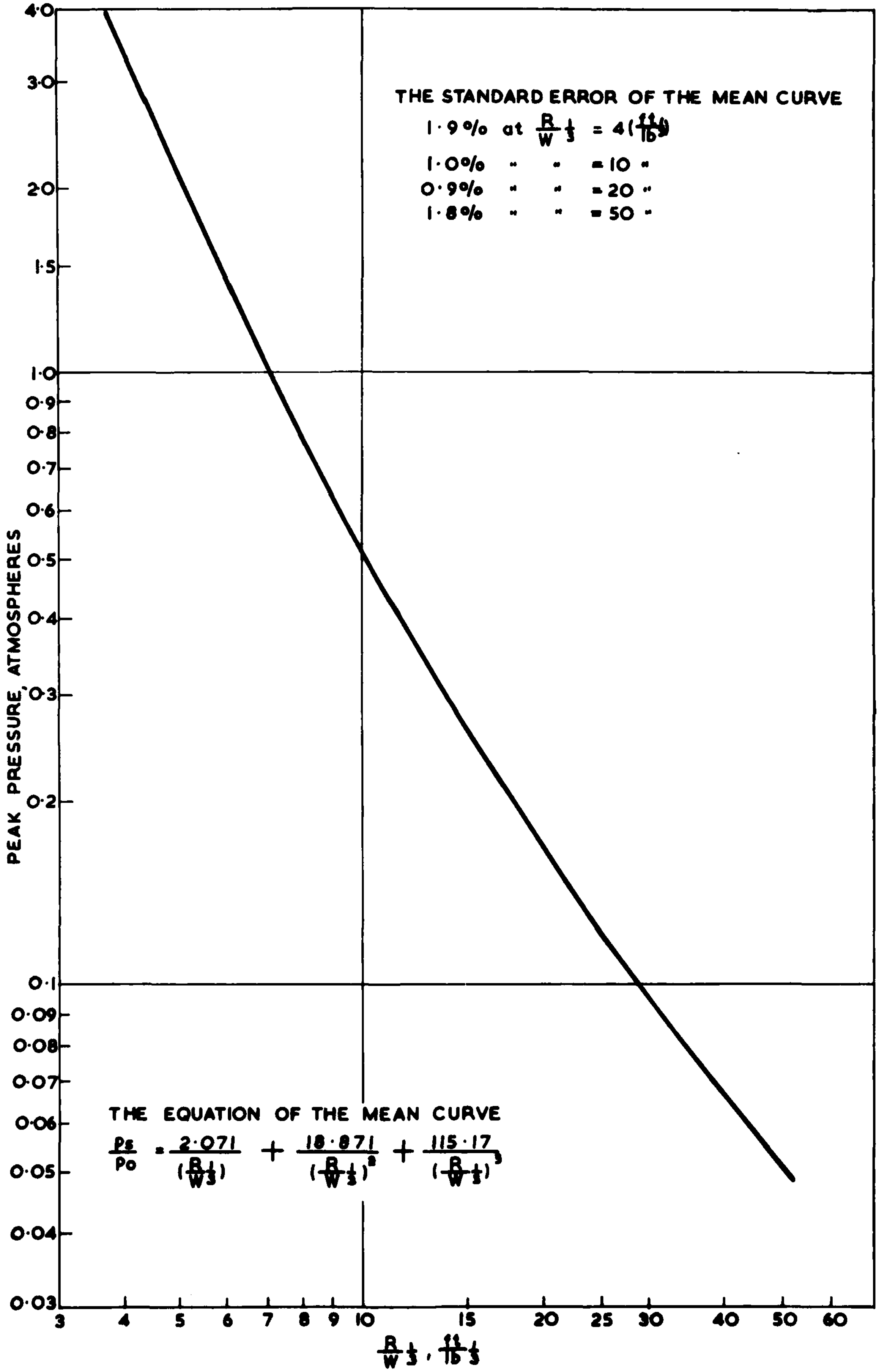


FIGURE 4(a) PEAK PRESSURE – DISTANCE FOR RDX/TNT 60/40

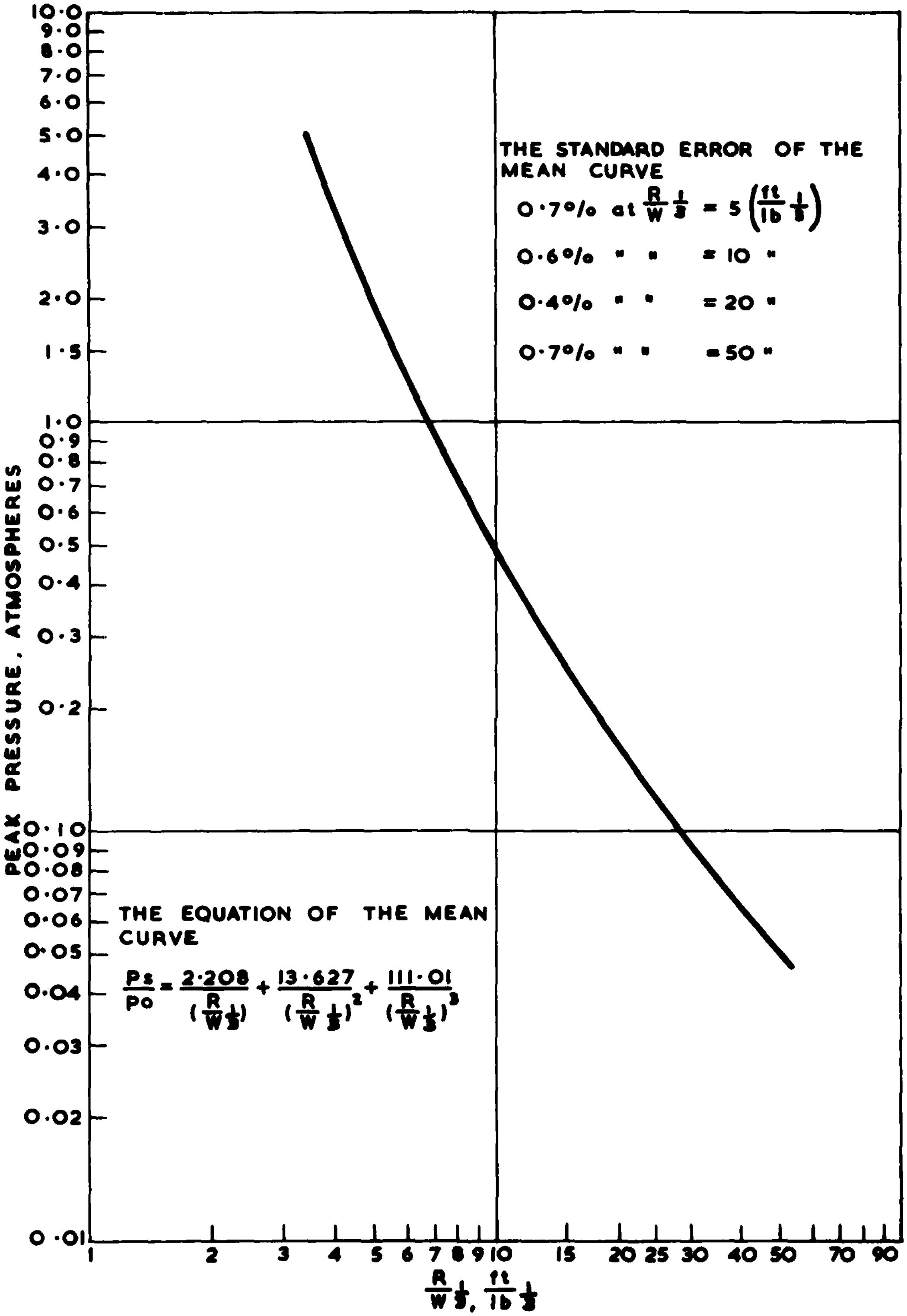


FIGURE 4 (b) PEAK PRESSURE – DISTANCE FOR TNT

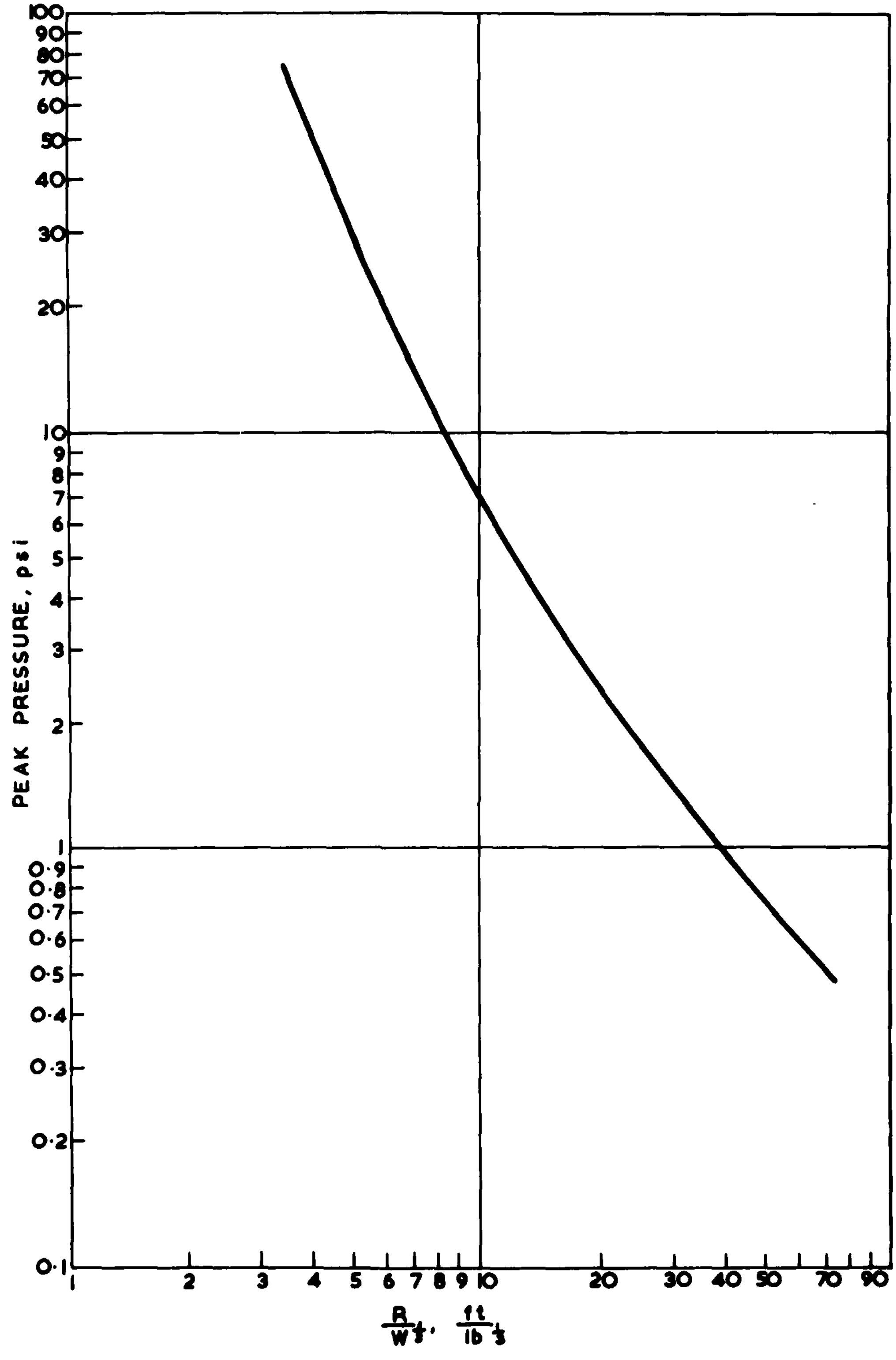


FIGURE 5. PEAK PRESSURE — DISTANCE FOR TNT

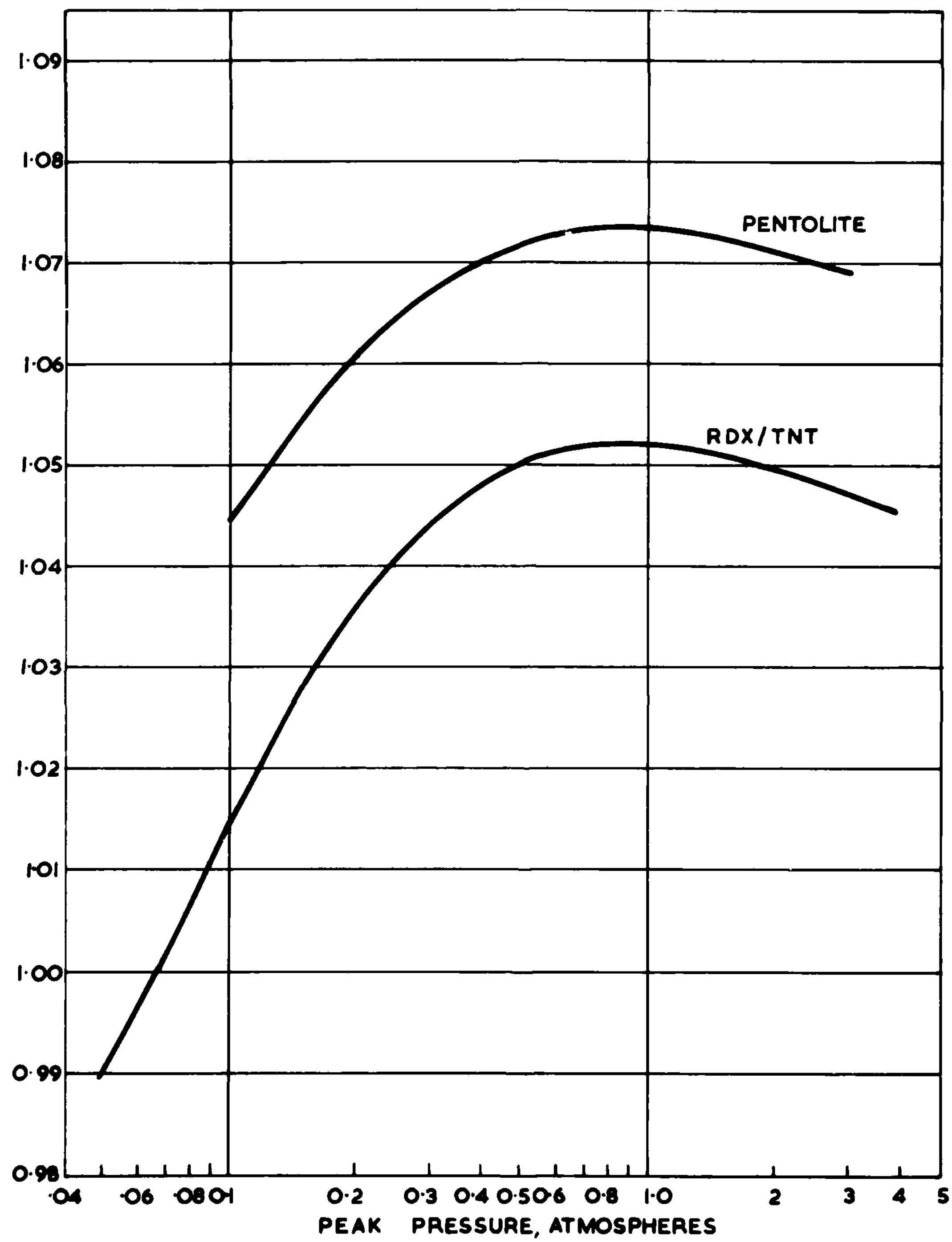


FIGURE 6. RATIO OF THE DISTANCES AT WHICH THE SAME PEAK PRESSURE IS PRODUCED BY DIFFERENT EXPLOSIVES.

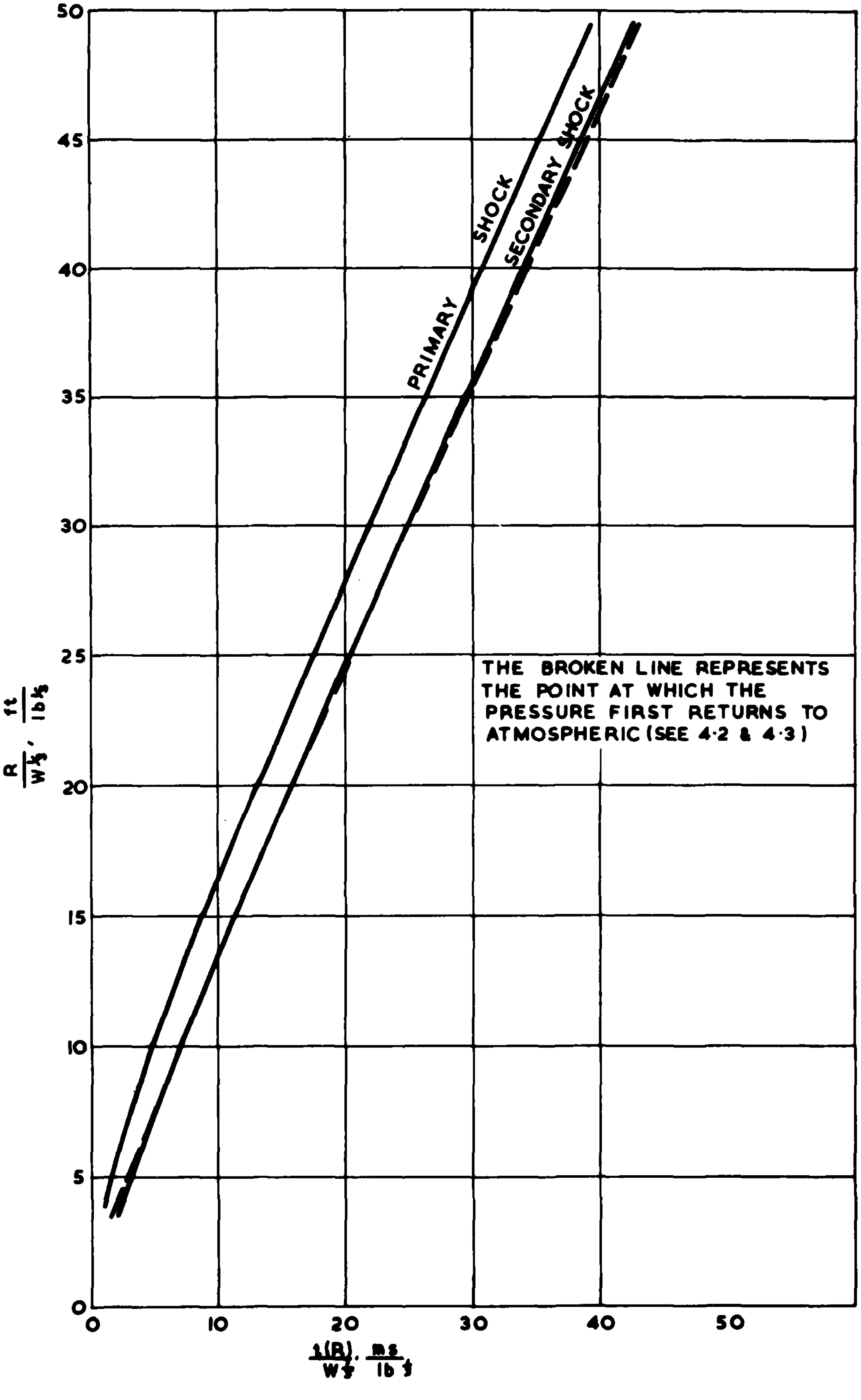


FIGURE 7 (g) RADIUS - TIME CURVES OF PRIMARY AND SECONDARY SHOCK FOR RDX/TNT 60/40

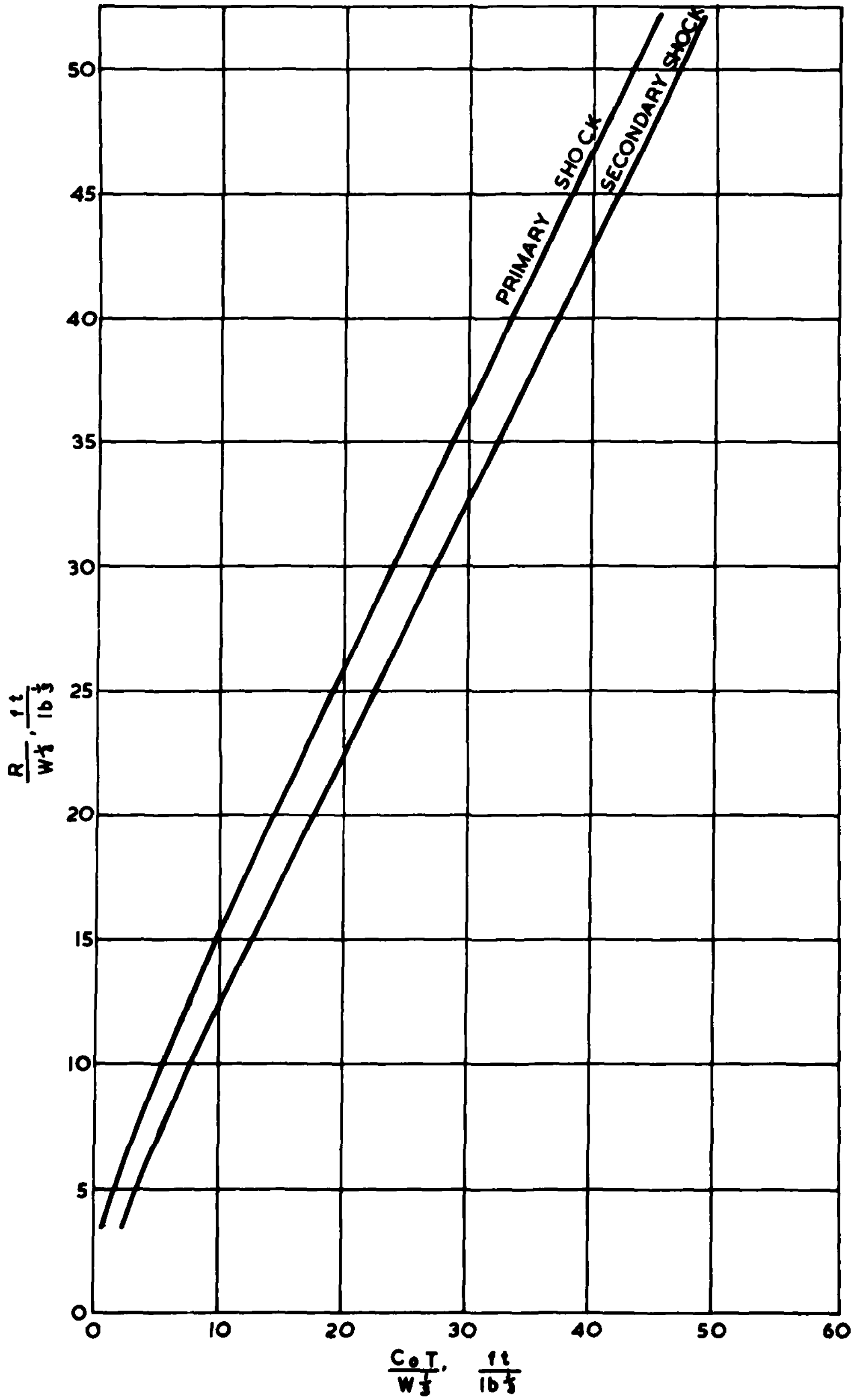


FIGURE 7(b) RADIUS-TIME CURVES OF PRIMARY AND SECONDARY SHOCKS FOR TNT

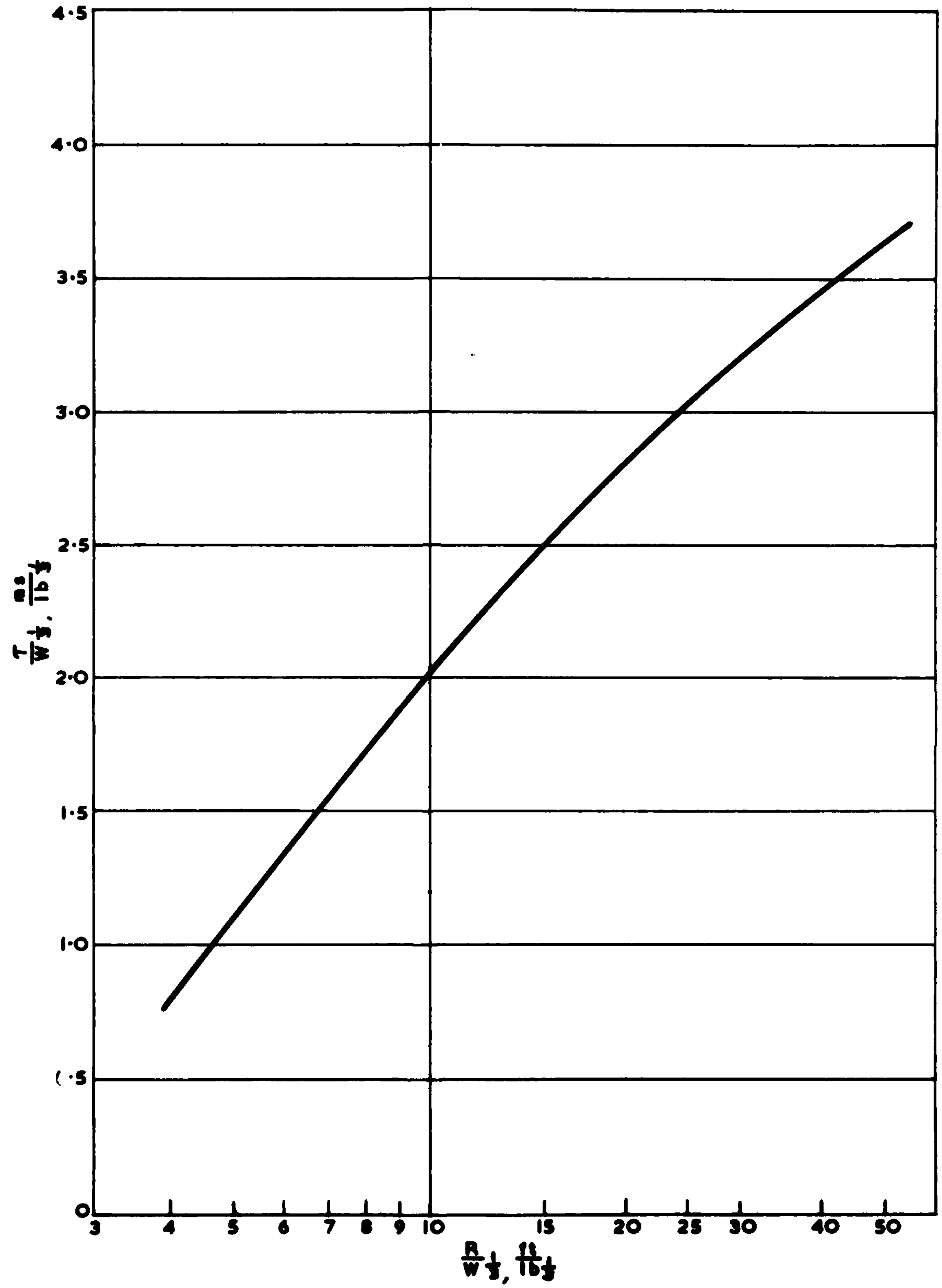


FIGURE 8(a) DURATION OF POSITIVE PHASE – DISTANCE FOR RDX/TNT 60/40

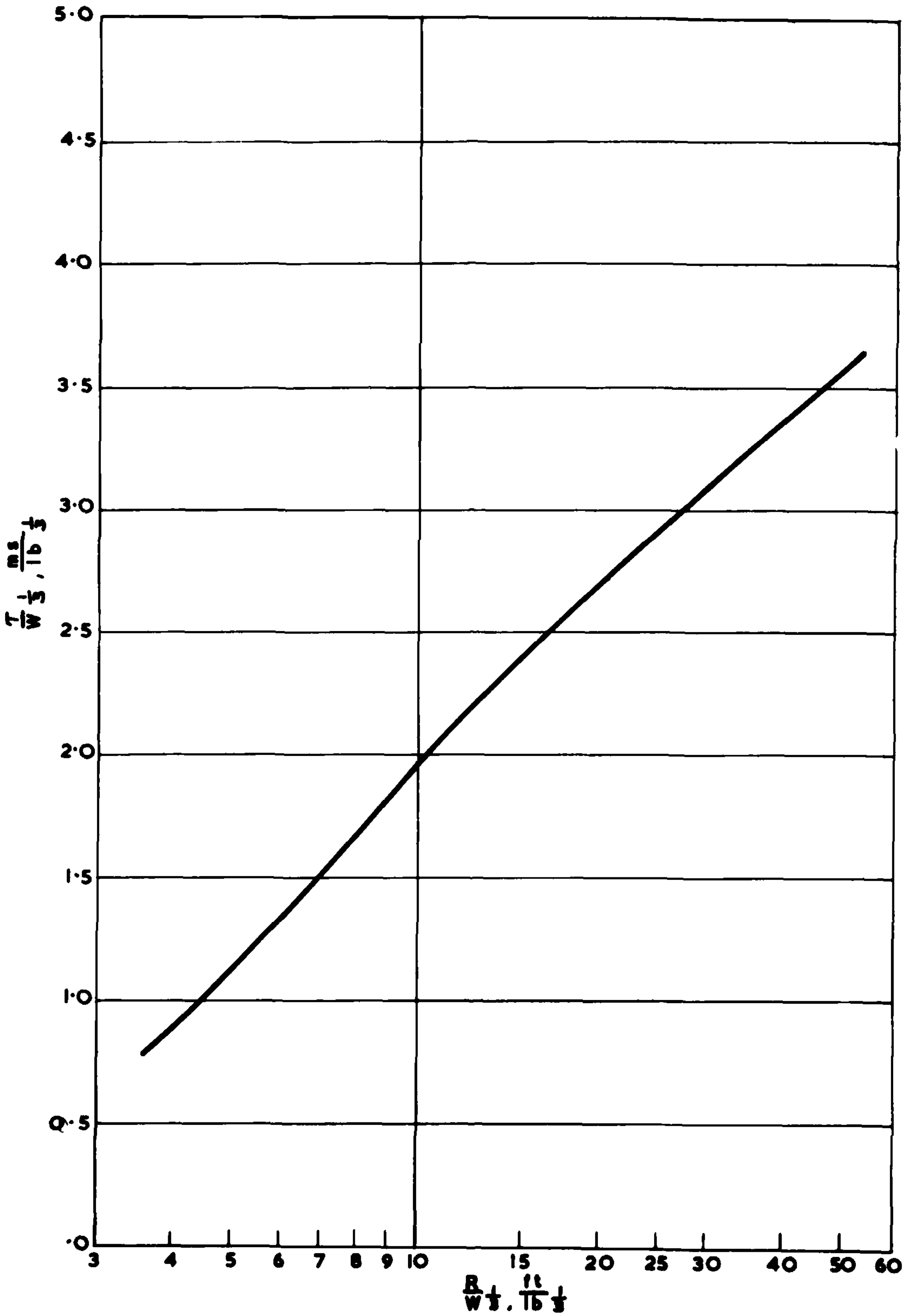


FIGURE 8(b) DURATION OF POSITIVE PHASE-DISTANCE FOR TNT

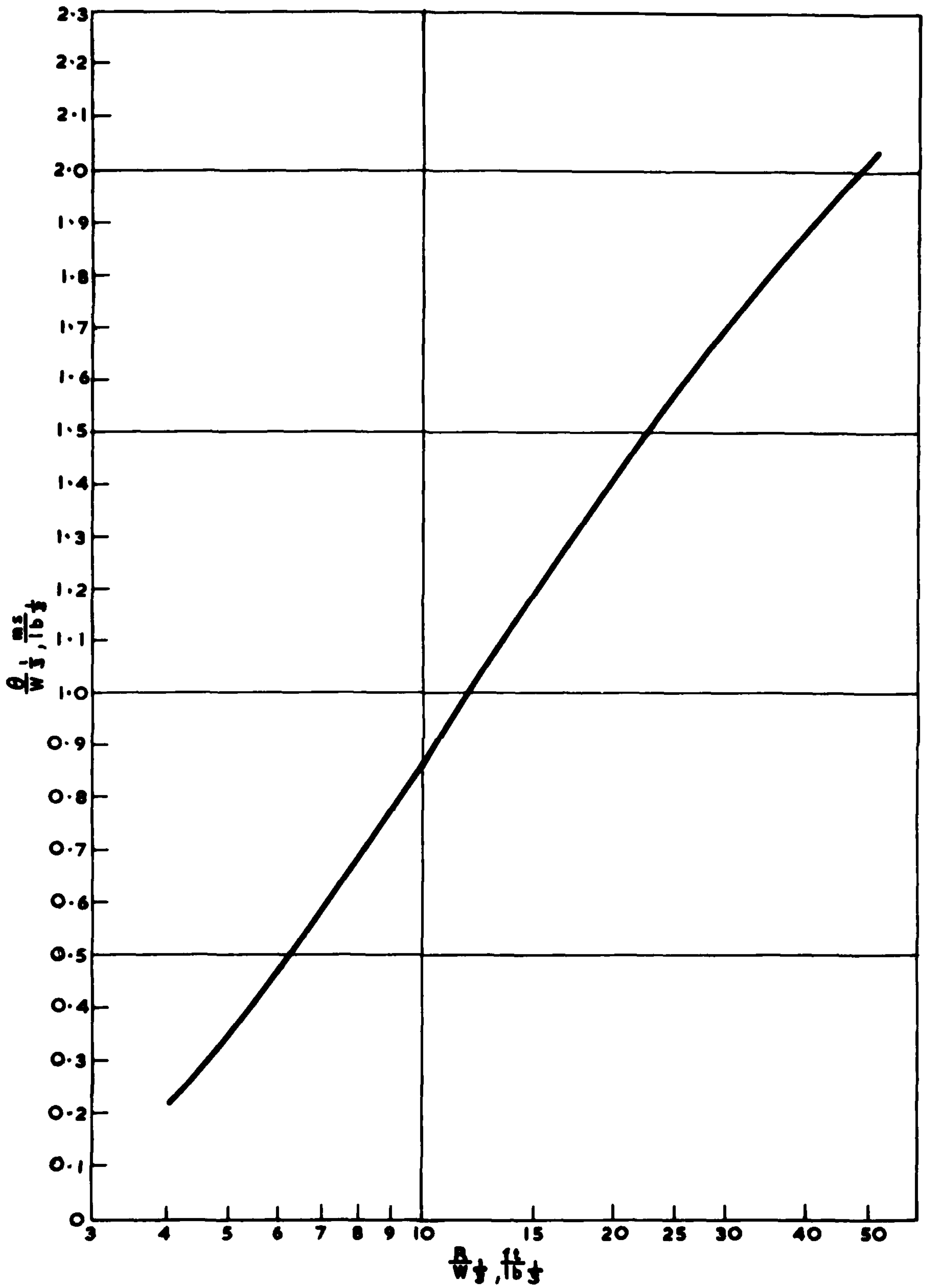


FIGURE 9(a) DECAY CONSTANT – DISTANCE, FOR RDX/TNT 60/40

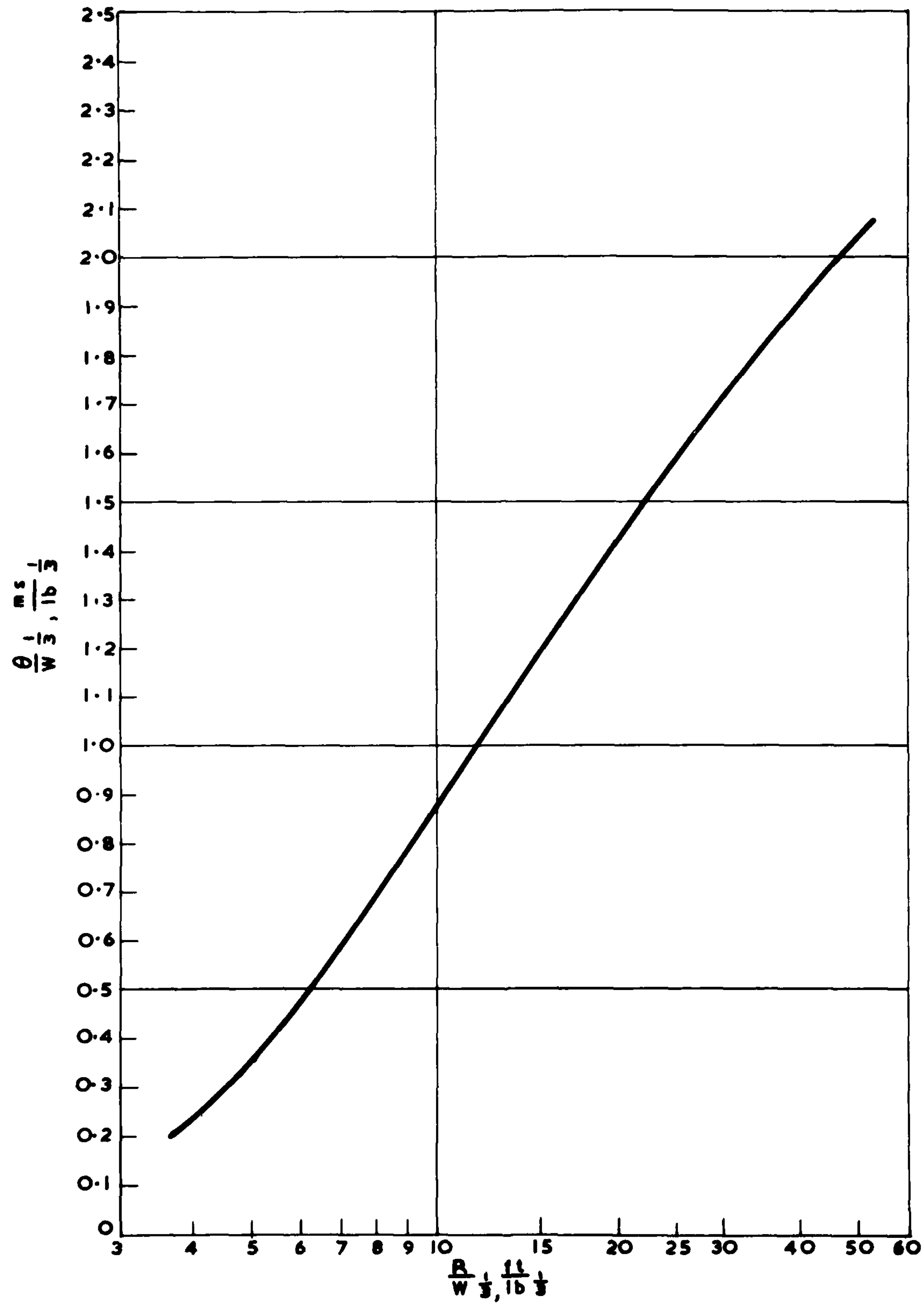


FIGURE 9(b) DECAY CONSTANT—DISTANCE FOR TNT

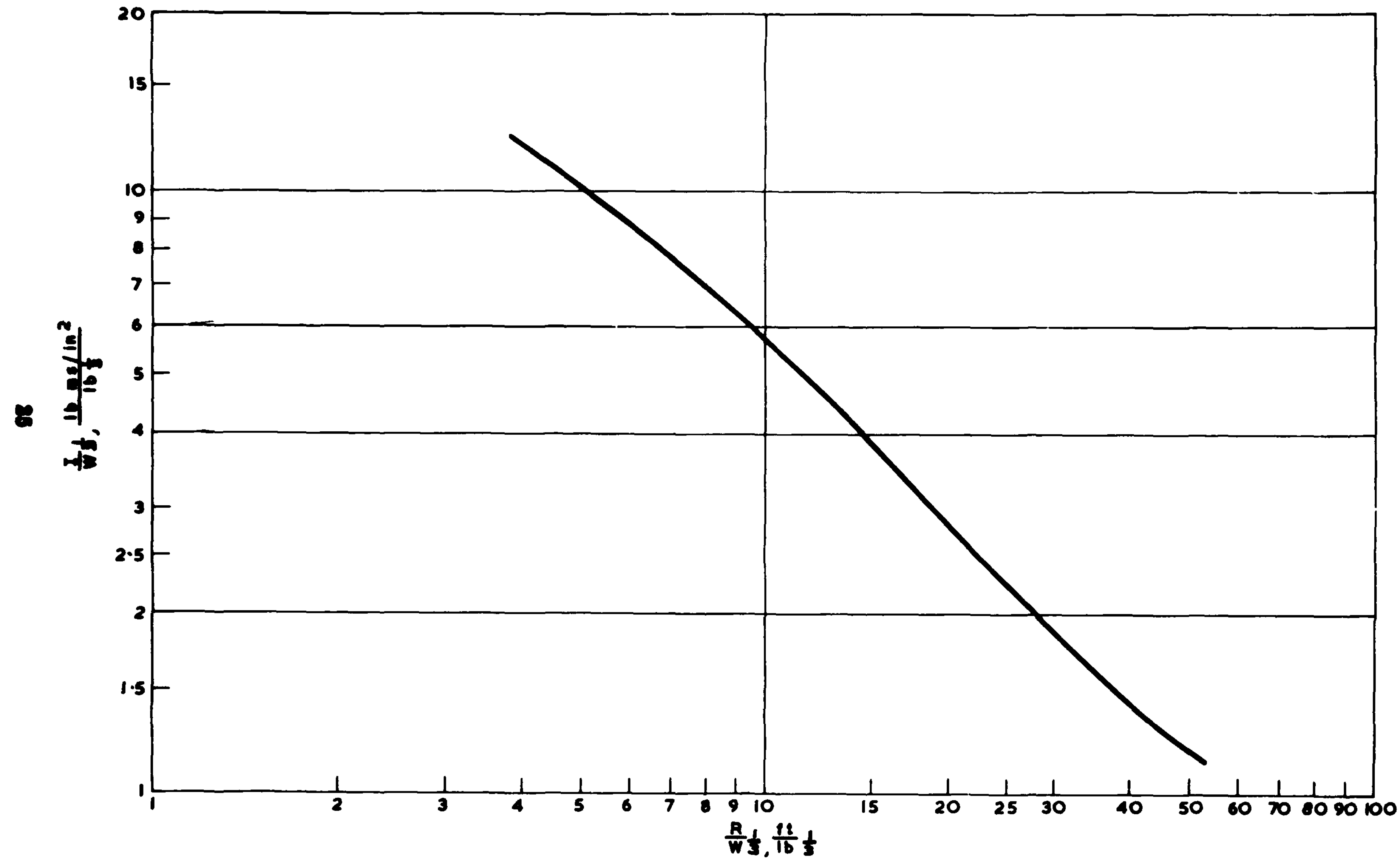


FIGURE 10 (a) POSITIVE IMPULSE – DISTANCE FOR RDX/TNT 60/40

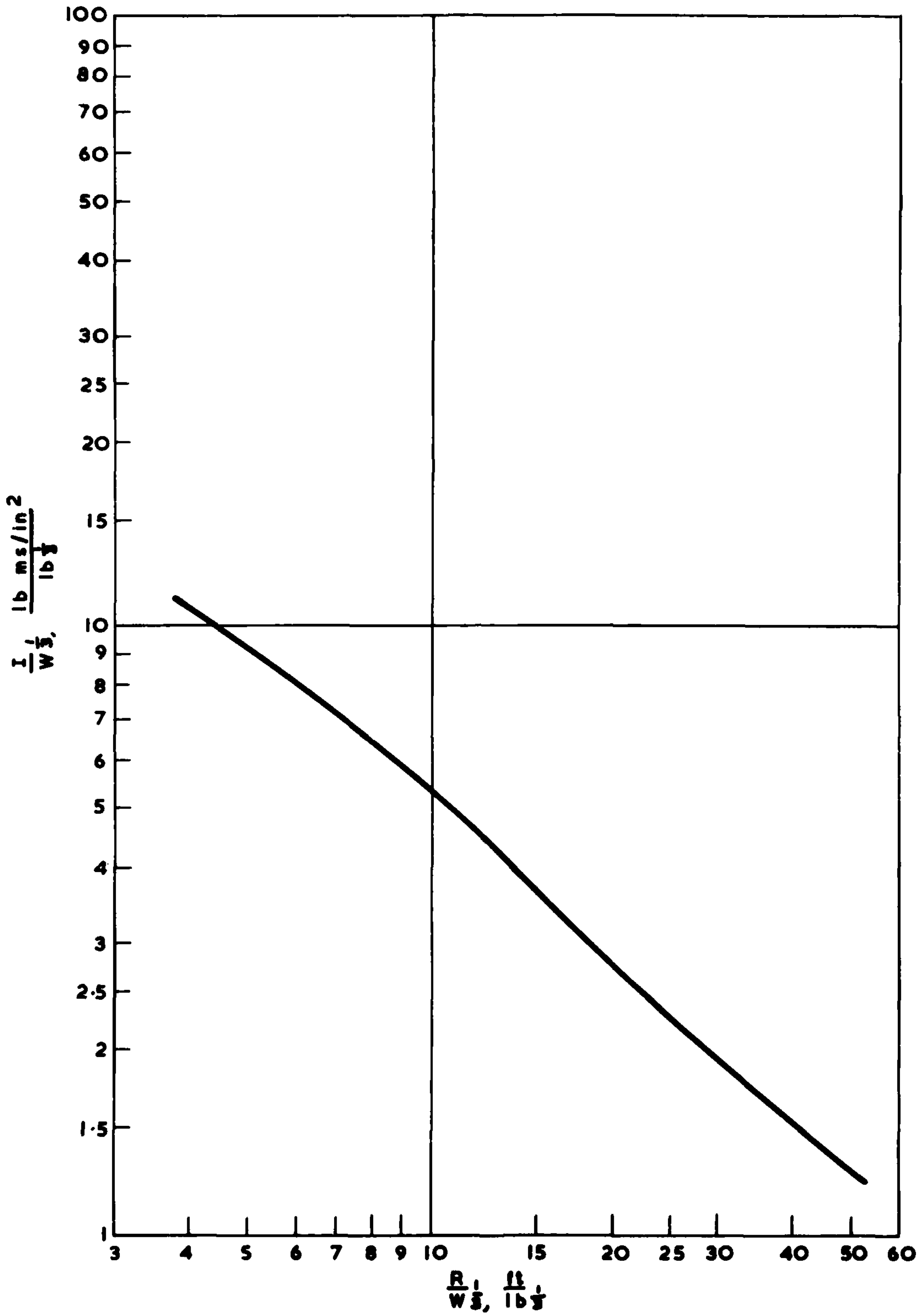


FIGURE 10 (b) POSITIVE IMPULSE—DISTANCE FOR TNT

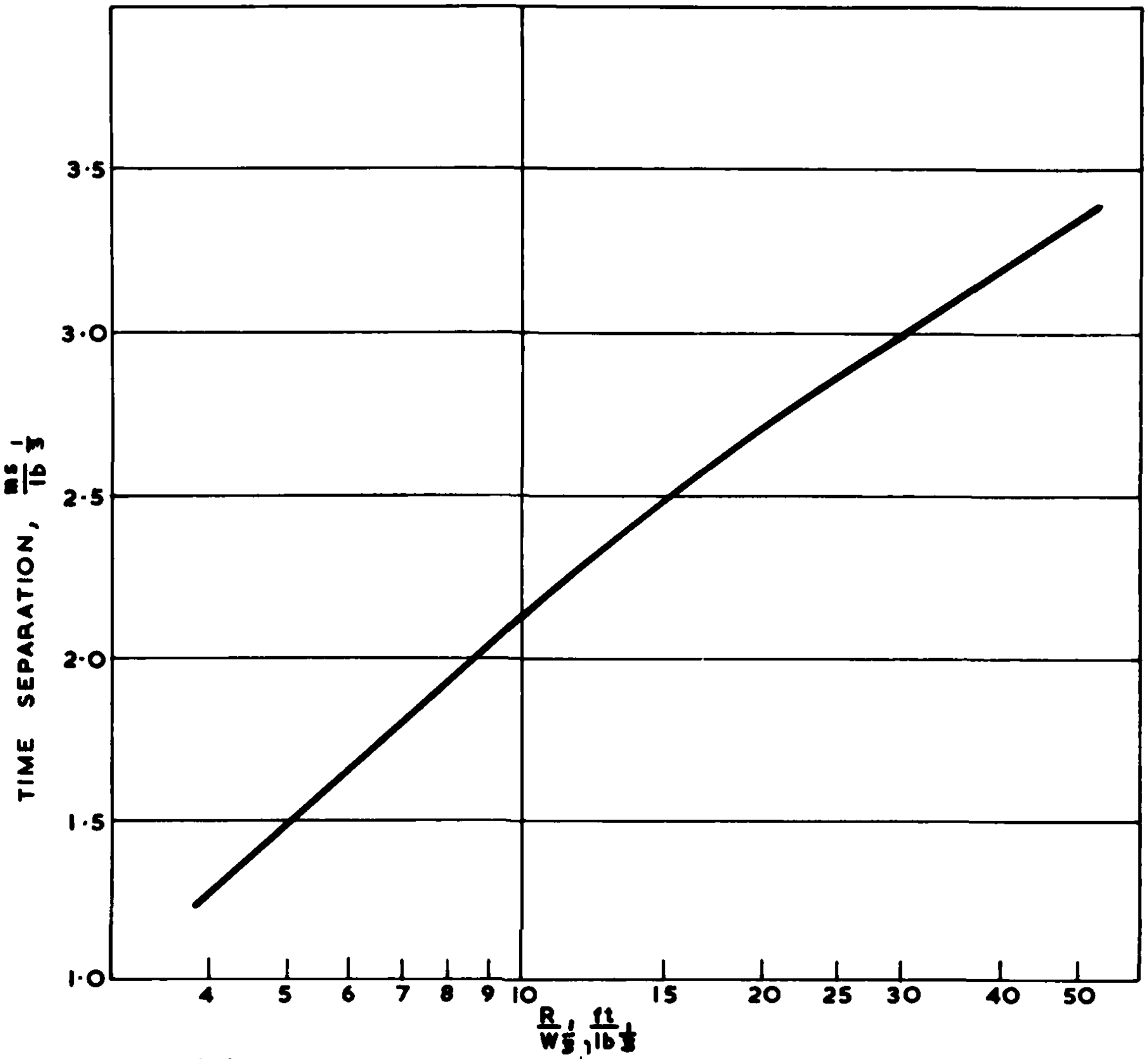


FIGURE 11(a) TIME SEPARATION OF PRIMARY & SECONDARY SHOCKS FOR RDX/TNT

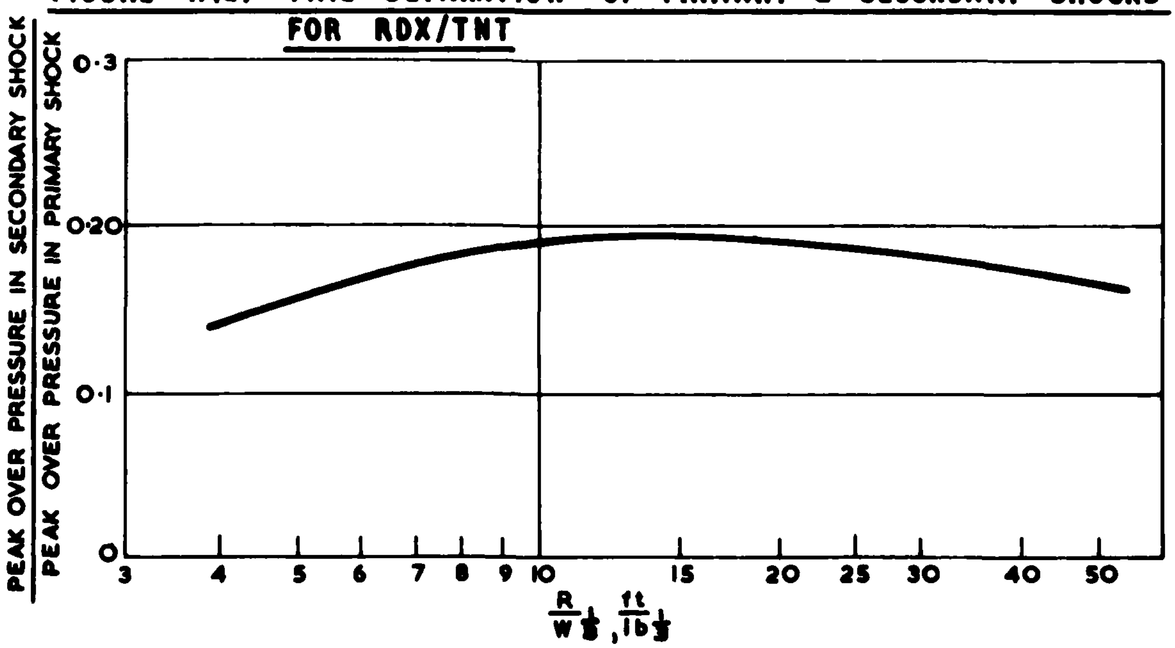


FIGURE 11(b) RATIO OF PEAK OVER PRESSURES IN PRIMARY & SECONDAY SHOCKS FOR RDX/TNT

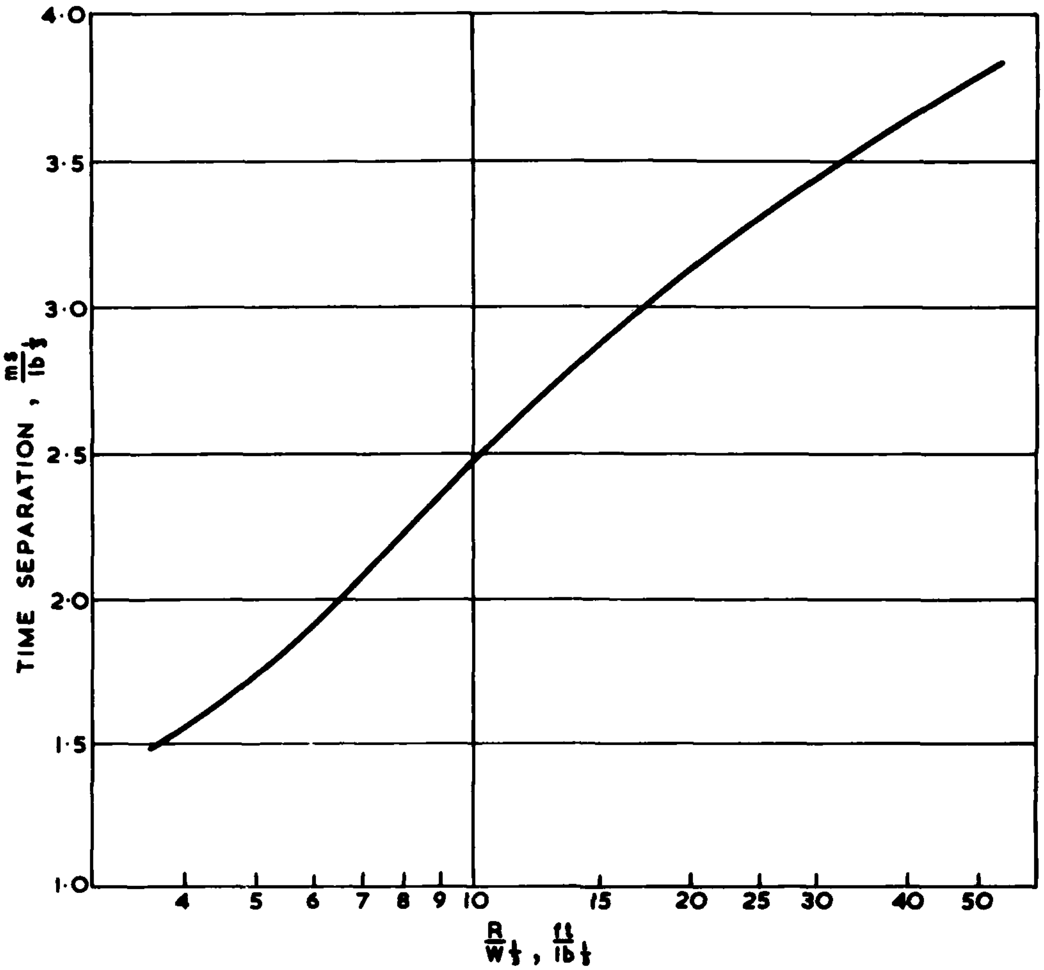


FIGURE 12 (a) TIME SEPARATION OF PRIMARY AND SECONDARY SHOCKS FOR TNT

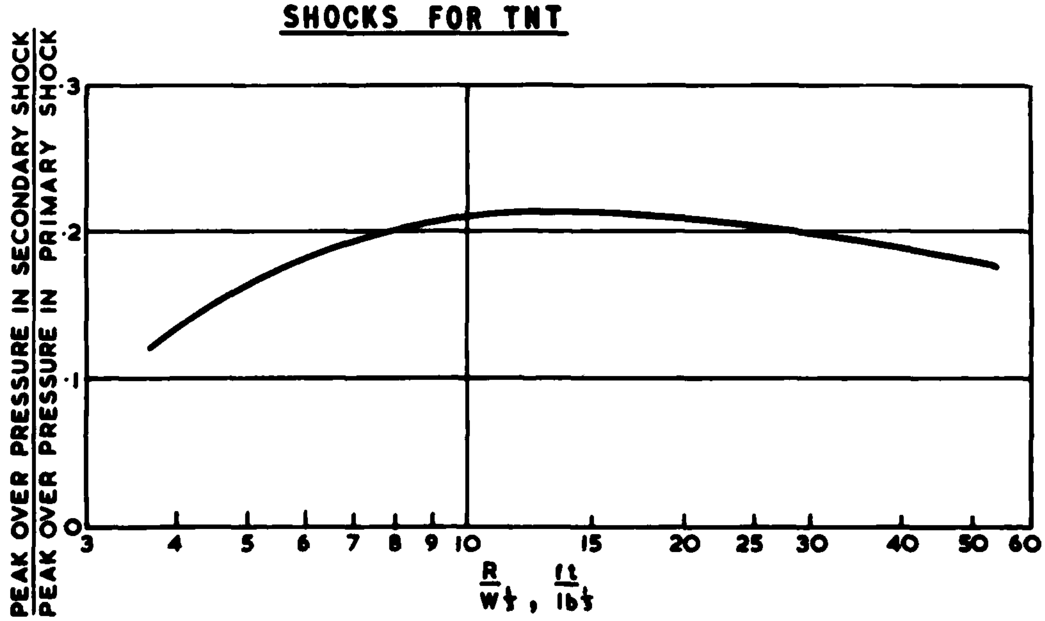


FIGURE 12 (b) RATIO OF PEAK OVER PRESSURE IN PRIMARY AND SECONDARY SHOCKS FOR TNT

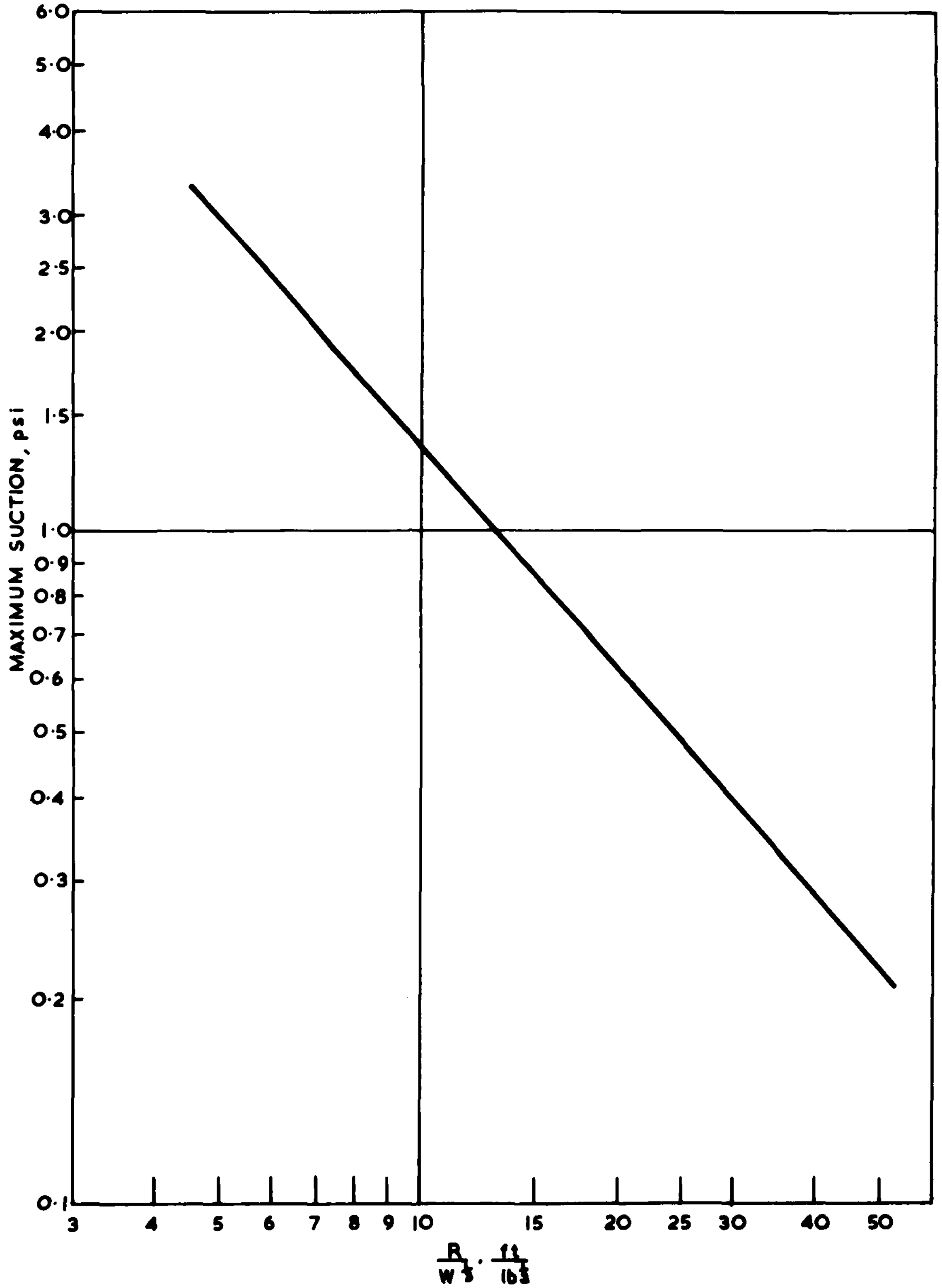


FIGURE 13(a) MAXIMUM NEGATIVE PRESSURE — DISTANCE

RDX/TNT 60/40

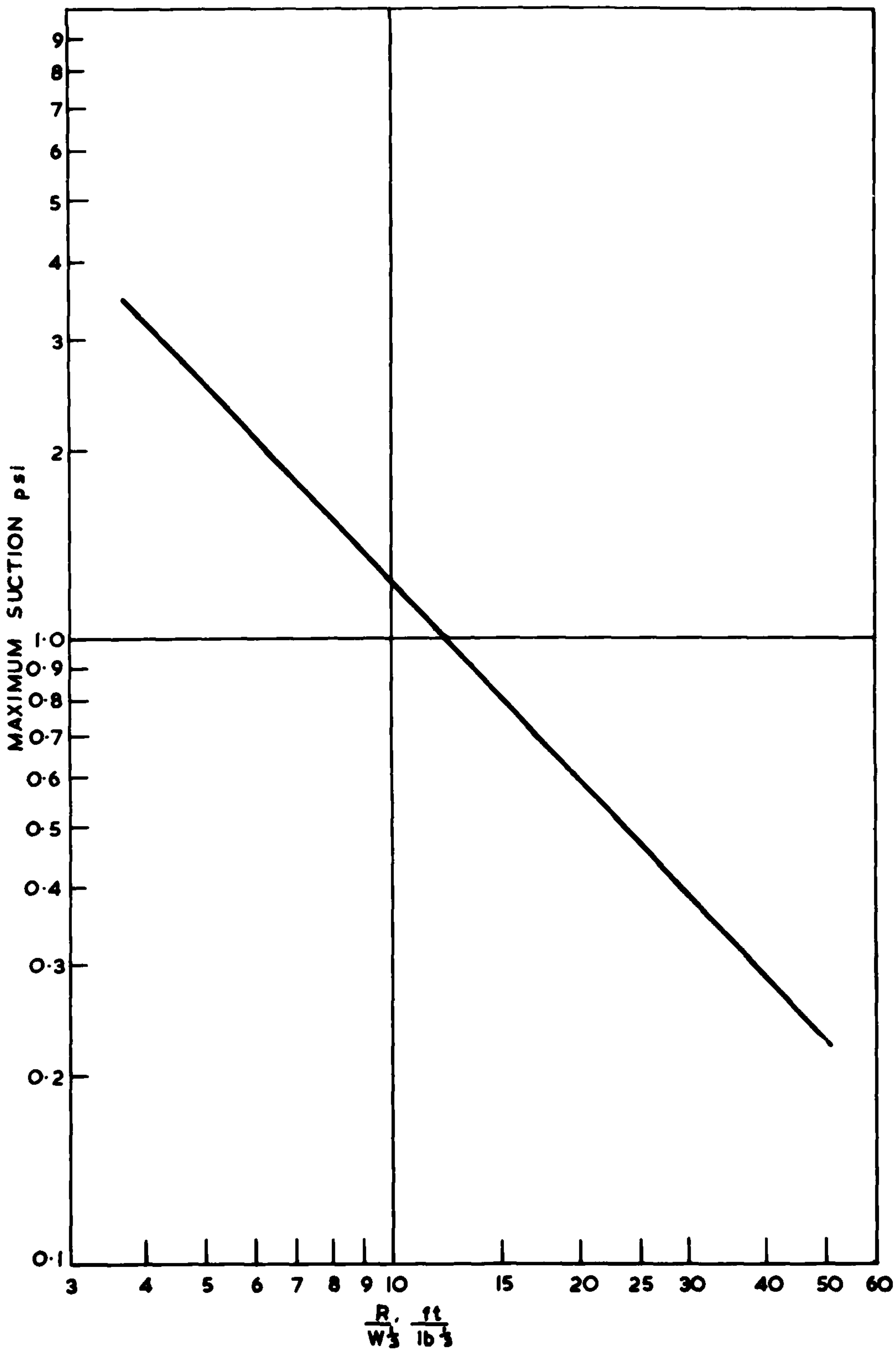
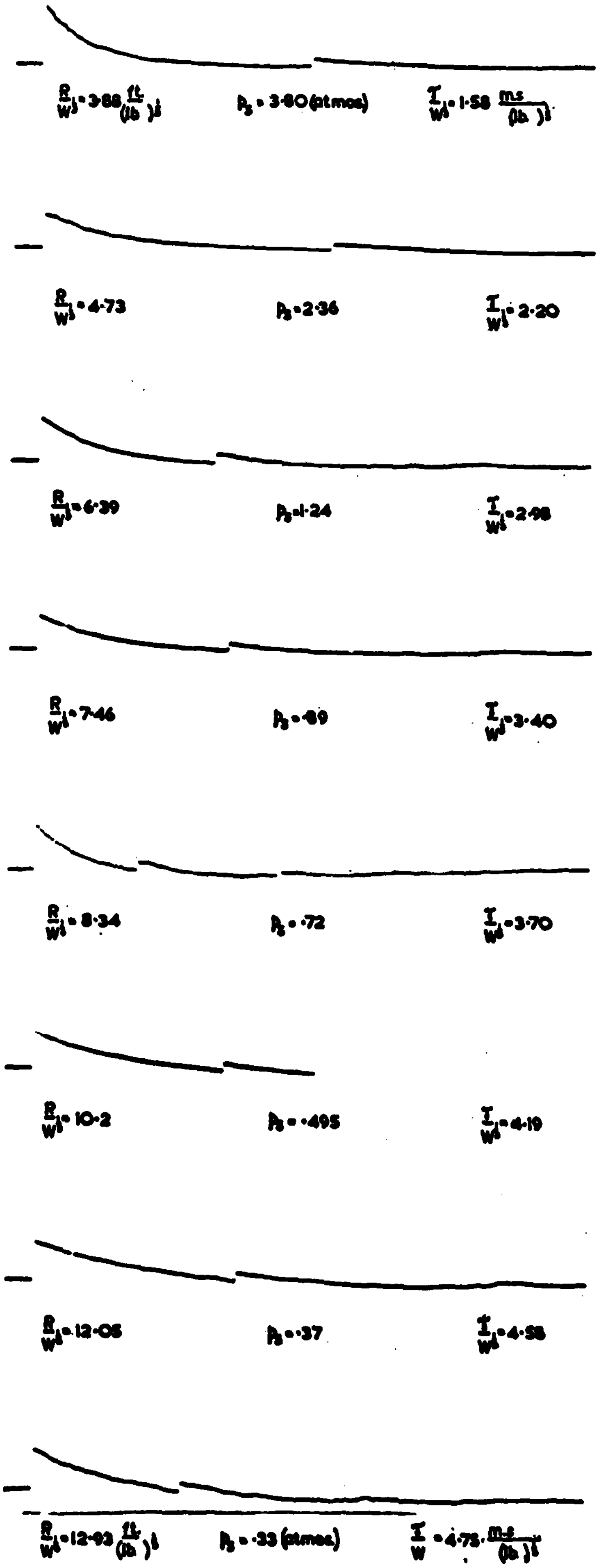


FIGURE 13 (b) MAXIMUM NEGATIVE PRESSURE — DISTANCE TNT



$\frac{R}{W^{1/3}}$ = 3·88 $\frac{ft}{(lb)^{1/3}}$
P_s = 3·80 (atmos)
$\frac{I}{W^{1/3}}$ = 1·58 $\frac{ms}{(lb)^{1/3}}$
$\frac{R}{W^{1/3}}$ = 4·73
P_s = 2·36
$\frac{I}{W^{1/3}}$ = 2·20
$\frac{R}{W^{1/3}}$ = 6·39
P_s = 1·24
$\frac{I}{W^{1/3}}$ = 2·98
$\frac{R}{W^{1/3}}$ = 7·46
P_s = ·89
$\frac{I}{W^{1/3}}$ = 3·40
$\frac{R}{W^{1/3}}$ = 8·34
P_s = ·72
$\frac{I}{W^{1/3}}$ = 3·70
$\frac{R}{W^{1/3}}$ = 10·2
P_s = ·495
$\frac{I}{W^{1/3}}$ = 4·19
$\frac{R}{W^{1/3}}$ = 12·05
P_s = ·37
$\frac{I}{W^{1/3}}$ = 4·58
$\frac{R}{W^{1/3}}$ = 12·93 $\frac{ft}{(lb)^{1/3}}$
P_s = ·33 (atmos)
$\frac{I}{W}$ = 4·75 $\frac{ms}{(lb)^{1/3}}$

FIGURE 14(a)

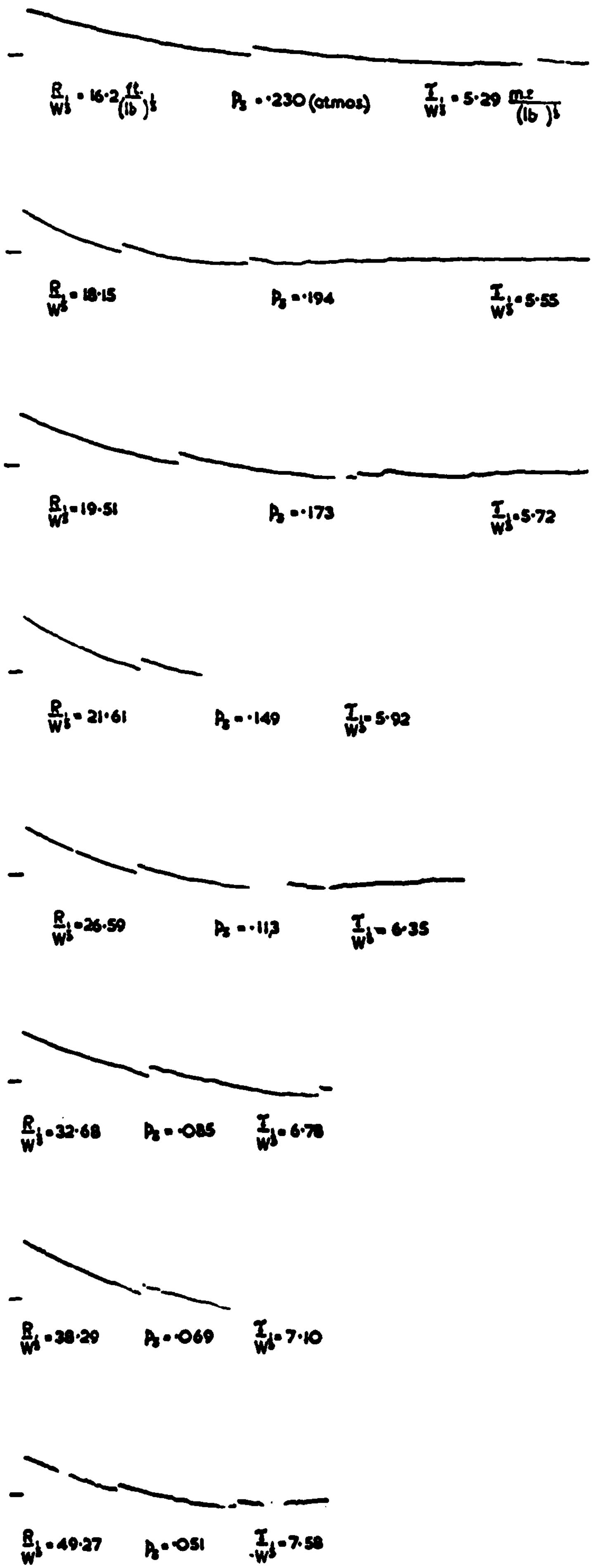

R/W^1/3 = 16·2 ft/(lb)^1/3
Ps = ·230 (atmos)
I/W^1/3 = 5·29 ms/(lb)^1/3
R/W^1/3 = 18·15
Ps = ·194
I/W^1/3 = 5·55
R/W^1/3 = 19·51
Ps = ·173
I/W^1/3 = 5·72
R/W^1/3 = 21·61
Ps = ·149
I/W^1/3 = 5·92
R/W^1/3 = 26·59
Ps = ·113
I/W^1/3 = 6·35
R/W^1/3 = 32·68
Ps = ·085
I/W^1/3 = 6·78
R/W^1/3 = 38·29
Ps = ·069
I/W^1/3 = 7·10
R/W^1/3 = 49·27
Ps = ·051
I/W^1/3 = 7·58

FIGURE 14(b)

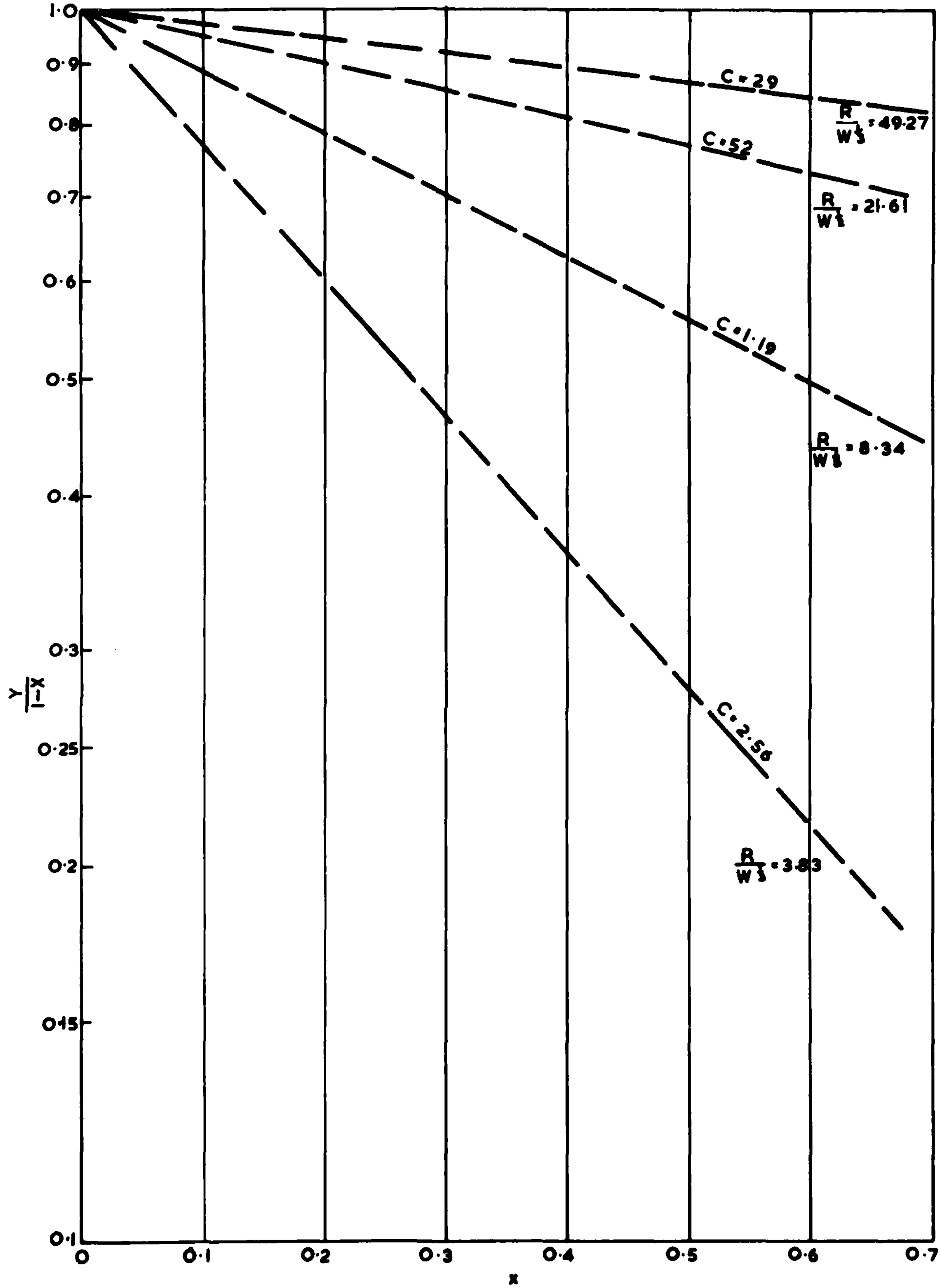


FIGURE 15 (a) LOG $\frac{y}{1-x}$ FUNCTION OF x FOR RECORDS 1,5,12,16 OF FIGURE 14 FOR RDX/TNT 60/40

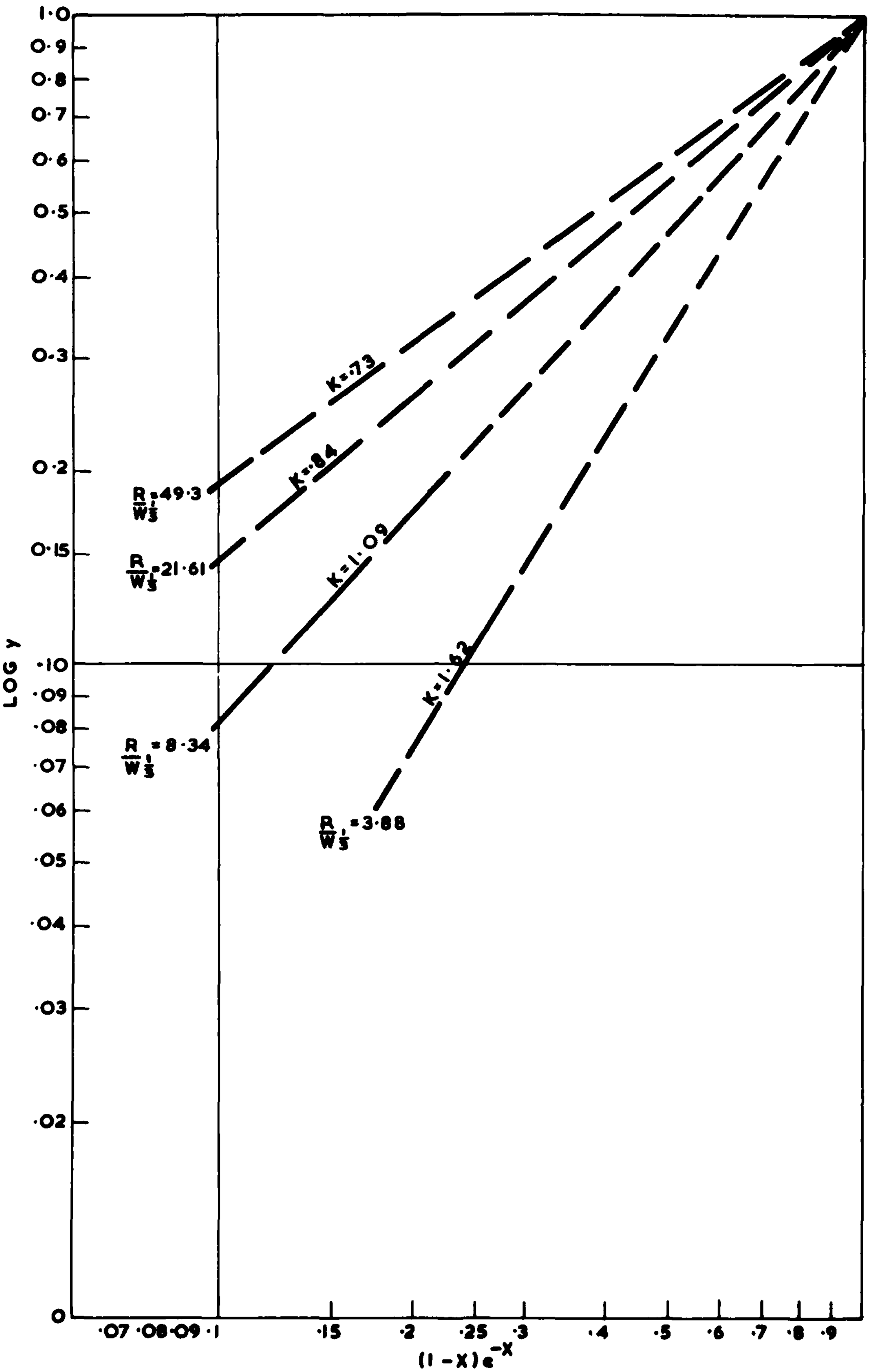


FIGURE 15 (b) LOG. y AS A FUNCTION OF LOG $[(1-X)e^{-X}]$ FOR RECORDS 1, 5, 12, 16, OF FIGURE 14 FOR RDX/TNT 60/40

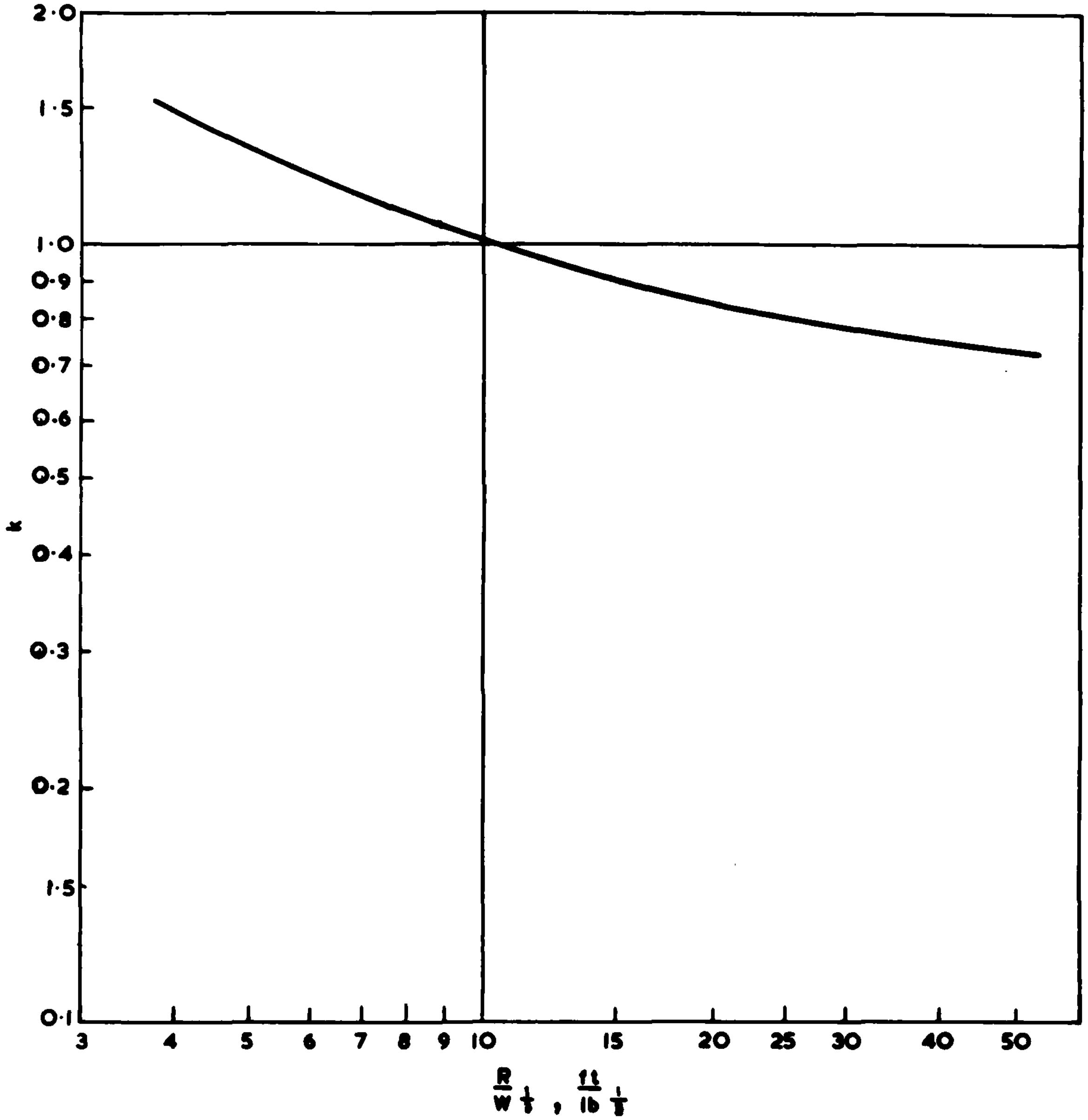


FIGURE 15 (c) VALUE OF k IN $y = [(1-x)e^{-x}]^k$ AS A FUNCTION OF DISTANCE FOR RDX / TNT 60/40

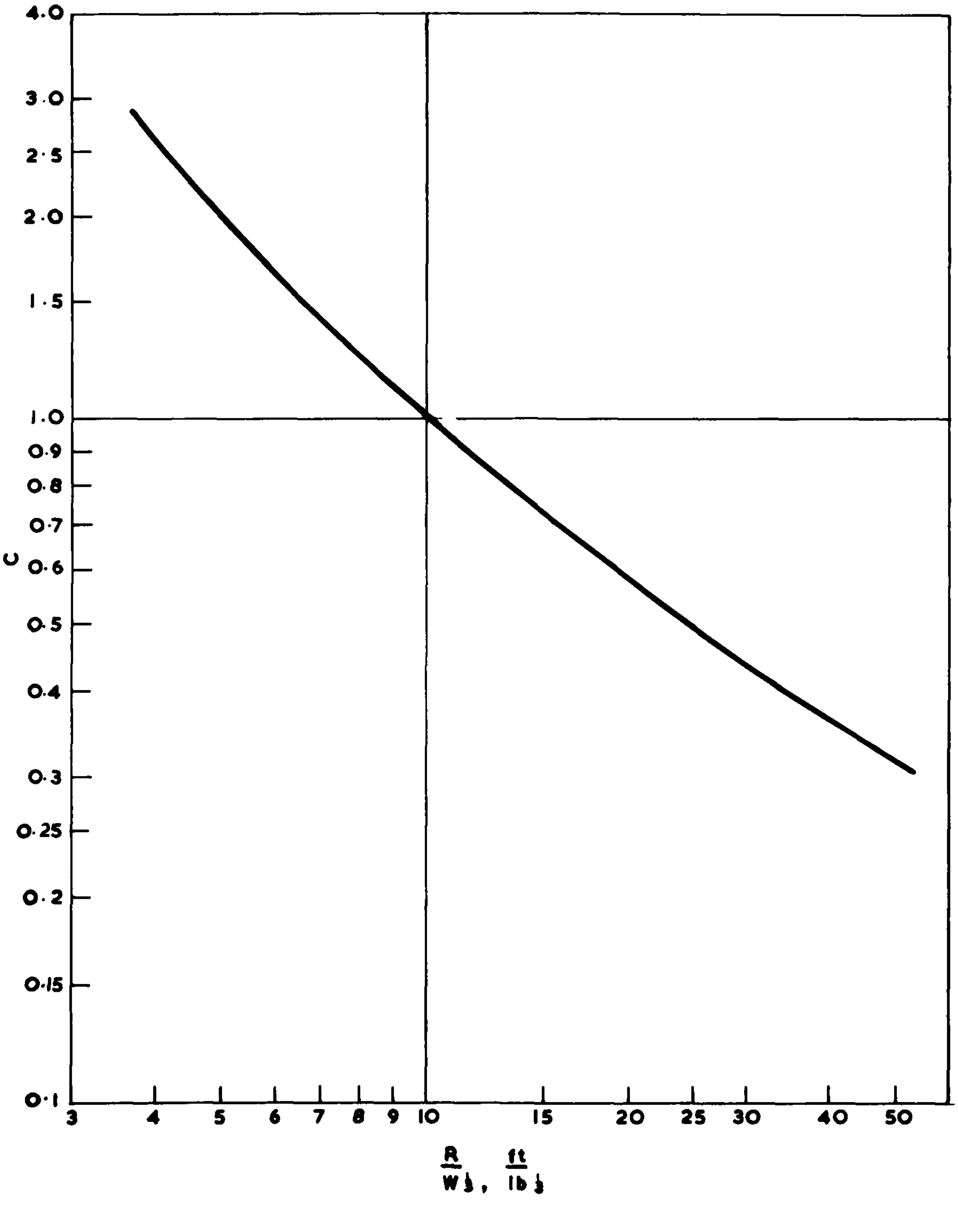


FIGURE 16(a) VALUE OF C IN $Y = (1 - x)e^{-ax}$ AS A FUNCTION OF DISTANCE FOR RDX / TNT 60/40

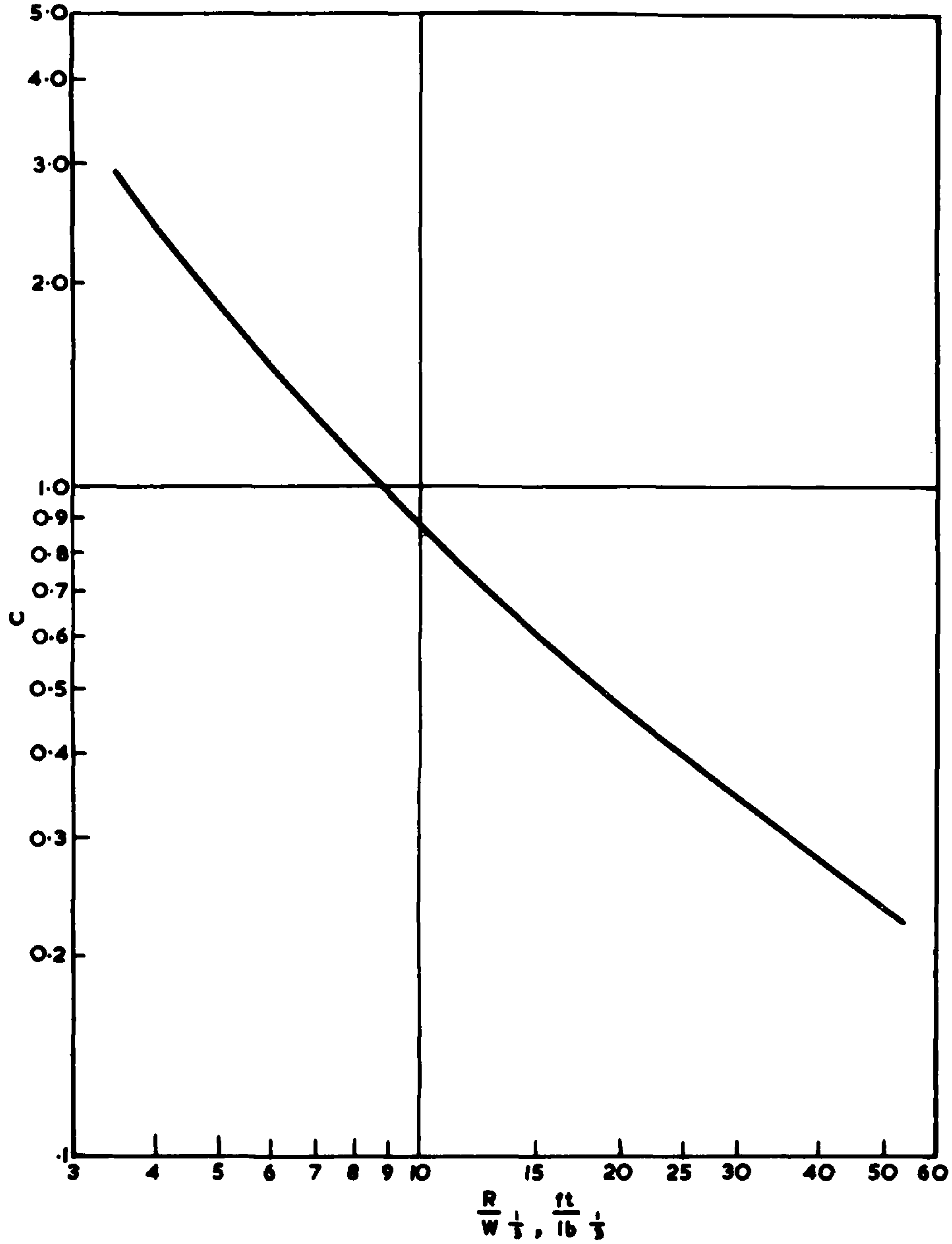


FIGURE 16 (b) VALUE OF C IN $Y = (1 - x)e^{-cx}$ AS A FUNCTION OF DISTANCE FOR TNT

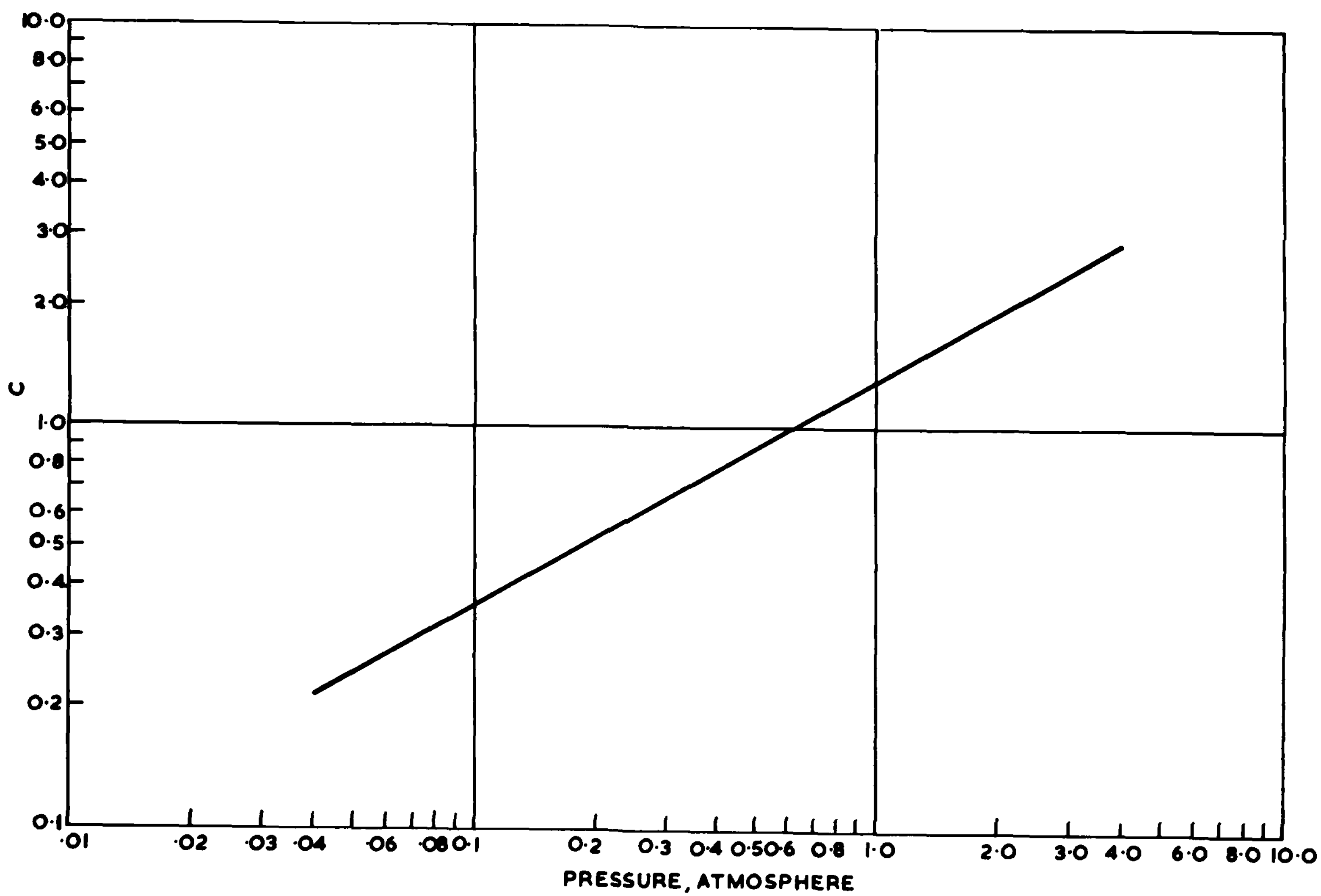


FIGURE 16 (c) VALUE OF C IN $Y = (1-x)\,e^{-cx}$ AS A FUNCTION OF PRESSURE FOR TNT

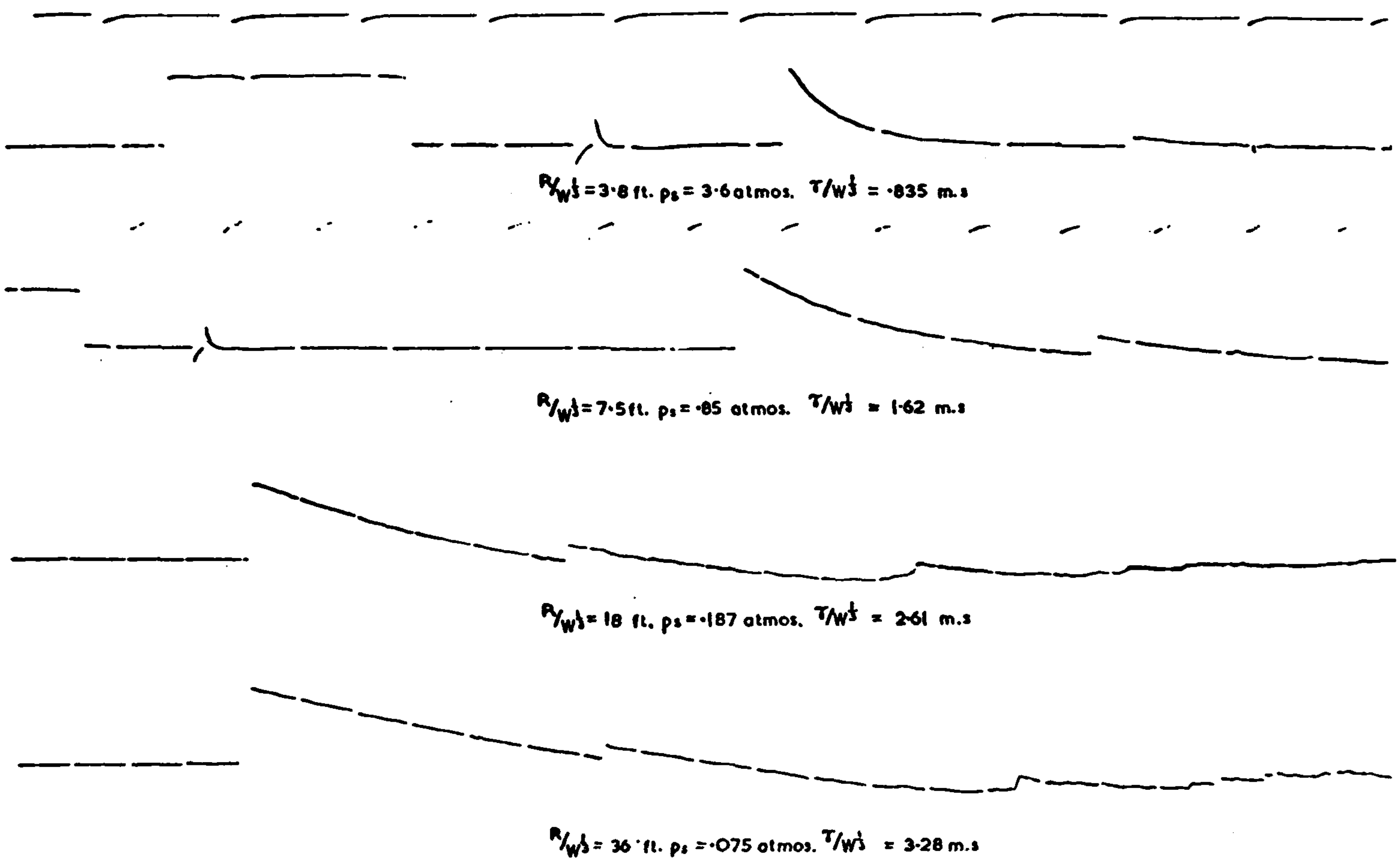


FIGURE 17. SOME TYPICAL RECORDS FOR TNT SHOWING FLASH MARKER PULSES AND BEAM BLANKING

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